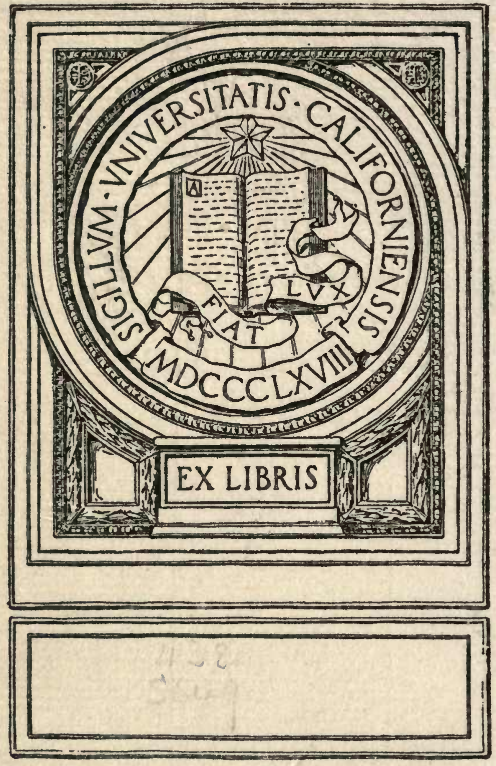
MINERALS & THE MICROSCOPE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MINERALS AND THE MICROSCOPE

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AND
THE MICROSCOPE

An Introduction to the
STUDY OF PETROLOGY

By

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PREFACE

THE object of this book is to help the beginner over his initial difficulties in the study of petrology. Teaching experience extending over some years has convinced me that the difficulties met by the student are far greater than is commonly supposed by those who have forgotten their own early trials, or whose mental equipment was such as to enable them to escape the pitfalls waiting for their less fortunate fellows.

Even a series of lectures by a teacher of undoubted qualifications is not sufficient; the subject matter is so new to most students that very few are able to absorb the facts as rapidly as they are placed before them. It is felt that a good course of lectures and practical work requires amplification by a book whose aim is to smooth over difficulties of this kind.

Amplification of such a course, then, is the chief aim of this work. It is hoped, also, that those who are not able to attend a course of lectures may profit by the instruction contained herein. A point of primary importance, however, is that this book is not intended to serve as a substitute for the examination of thin sections.

The list of minerals described is far from being complete, but some care has been expended in the selection and arrangement of those dealt with, and it is hoped that when a student has worked through them, he will be competent to, and desirous of, examining the minerals less commonly met with in thin section.

The section on petrology is designed to bridge over the gap usually left by text books on the subject, and should be used in conjunction with such a book as Harker's Petrology for Students, or Hatch's Text-book of Petrology.

It has been found necessary to assume that students have a knowledge of elementary physics and of crystallography. The former may quite safely be assumed, but the latter assumption is probably more dangerous; a good and simple description of the subject, however, will be found in the latest edition of Rutley's Mineralogy, a book which will be found extremely useful in other respects.

My thanks are due to the Rector of the Imperial College and to Professor Watts for permission to use the apparatus of the college in the preparation of the photographs reproduced in this book, also to my colleague, Mr. H. H. Read, for reading through the proofs and for many helpful suggestions.

H. G. SMITH.

April, 1914.

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DESCRIPTION OF PETROLOGICAL MICROSCOPE

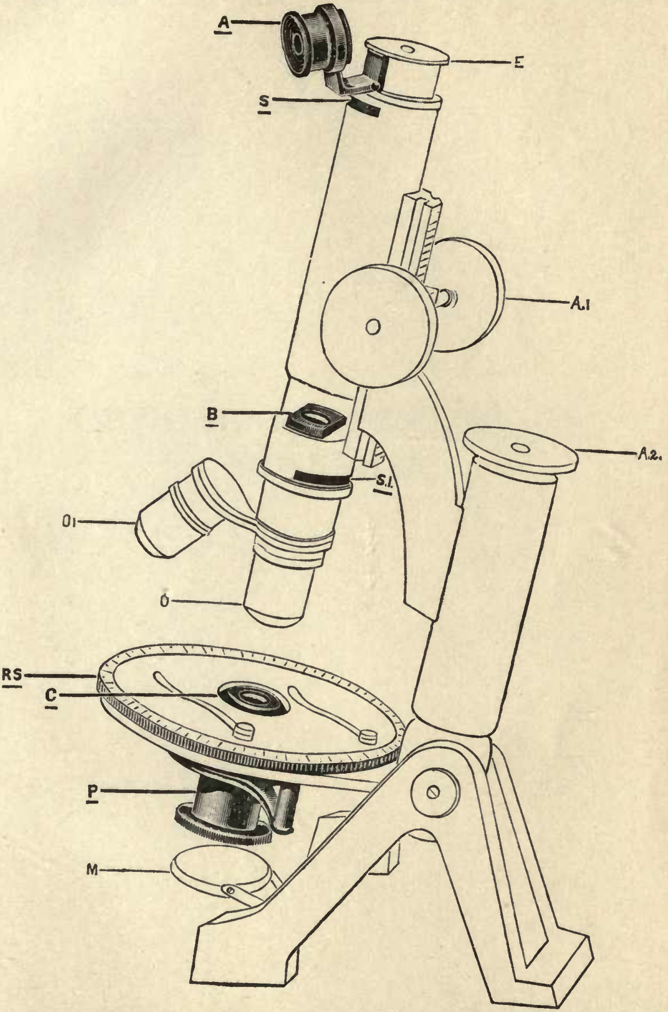
THE foot forms a support for the whole instrument, the pillar being attached to it by means of a joint which allows movement on a horizontal axis. The pillar supports the tube at its upper end, and the stage, RS, at the lower end; the adjustments, A_1 and A_2, give rise to a movement of the tube with reference to the pillar so as to cause the objective, O, to approach or recede from the stage. O and O_1 are the two objectives; these have different magnifying powers, and either may readily be placed in line with the tube so as to come into use. The eyepiece, E, is a system of lenses fitting into the upper end of the tube; it brings the magnified image to a focus when the objective is properly adjusted.

RS, the rotating stage, supports the microscope slip, which is held in position by means of the two clips. The stage is graduated into degrees, and may be rotated through a known angle, the angle being read by means of a fixed point or a vernier attached to the pillar. The mirror, M, receives light from some source of illumination, and when placed at the proper angle, transmits the light along the axis of the instrument to the eye.

The polariser, P, is a Nicol's prism placed beneath the stage; it is capable of rotation on its own axis, and may be swung aside when not required. A, the analyser, is also a Nicol's prism which is capable of rotation; when required, it is swung into position above the eyepiece.

Additional fittings, the object of which is to produce interference figures, are B, the Bertrand lens, and C, the converging lens. The converging lens is placed between the polariser and the stage, the Bertrand lens in the tube above the objective. The latter consists of a converging lens of the required focal length; it may be mounted in a carrier, so as to enable it to slide in and out of the tube as required, or may be fitted in the lower end of a draw-tube. The illustration shows the tube cut away in order to indicate the position of this lens when in use.

S and S_1 are two slots, into which the wedge or mica plate may be inserted when determinations of " sign " are to be made.



The above illustration shows at a glance the essential features of a Petrological Microscope by means of the letters underlined and the detail work. It will be found that the parts A. B. S. and S1 are differently situated in the microscopes supplied by various manufacturers.

OPTICAL PROPERTIES OF MINERALS

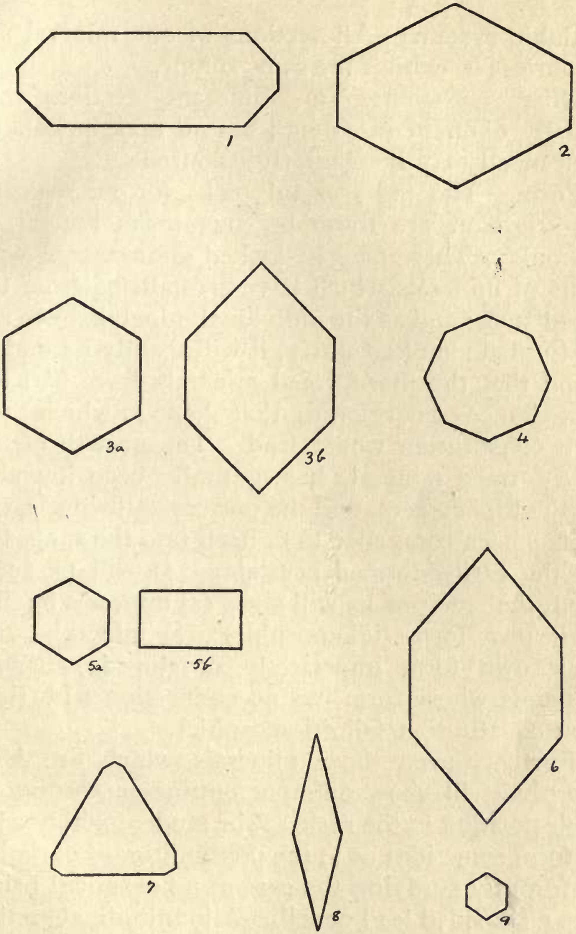
CHARACTERS OF MINERALS IN ORDINARY TRANSMITTED LIGHT

THE first examination of the section should be made with the one inch objective; both polariser and analyser being swung out of the axis of the instrument.

As a rule, it will be seen that the thin section is made up of several minerals, some transparent, others opaque. For the present we shall confine our attention to the study of those minerals that transmit a certain amount of light; a method for the examination of opaque minerals will be described later.

Colour.—The light transmitted by the different minerals varies both in amount and kind; some minerals are almost opaque, others perfectly transparent. In some cases, the whole of the constituents of white light are allowed to pass through; these minerals are colourless. Other minerals, however, absorb some portion of the spectrum, with the result that the light reaching the eye has a certain colour—the colour complementary to that absorbed. This colour supplies us with the first means of distinction between the rock-forming minerals.

The section will probably contain several fragments of any particular mineral, and the student will naturally expect that all these fragments will exhibit the same colour, or will agree in being colourless; but it must be realised that, while this may be the case, it is not necessarily so. Variation in the colour of the different fragments is intimately related to the crystal symmetry. Should the mineral in question crystallise in the cubic system, all the fragments present in the section will be either colourless or will transmit the same colour; a good example is the mineral garnet, the common varieties of which transmit a pink colour. On the other hand, biotite, crystallising in the monoclinic system, supplies us with an example of a mineral which varies in colour according to its orientation in the section. The different fragments occupy all possible positions in the rock from which the section is cut; consequently a section supplies numerous cases. Crystallographically, no two of these are identical, and each case has its own absorption. The result is that the different fragments of this mineral exhibit very different shades of brown. It will be seen that we must rely on other characters to demonstrate that such fragments are identical in composition. There are many cases, however, even in the same system, in which all sections of a coloured mineral have much the same shade; a good example is common augite. Again, the mineral muscovite, also crystallising in the monoclinic system, is typically colourless in all its sections. The relationship of colour in thin section to crystal symmetry may be summarised as follows :—



1. Augite. Transverse section.
2. Hornblende. Transverse section.
3*a*. Quartz—Basal section.
3*b*. " Vertical "
4. Leucite.
5*a*. Nepheline—Basal section.
5*b*. " Vertical "
6. Olivine.
7. Tourmaline—Basal section.
8. Sphene.
9. Apatite—Basal section.

Cubic system:—All sections of one mineral are colourless or exhibit the same colour.

Other systems:—The different sections are usually different in colour; but all may be colourless, or all may be similarly coloured.

Form.—The most useful rocks for microscopic investigation are those igneous rocks known as plutonic. These may be looked upon as aggregations of minerals which have crystallised from the fused state; and as the individual minerals have not all formed simultaneously, it will readily be understood that the first-formed minerals have had the best chance of developing that shape to which their own constitution would lead. The growth of the later-formed minerals has naturally been impeded by the first comers, and the one crystallising last of all has been compelled to fit itself into the space left by the earlier-formed crystals. It will be seen, then, that such rocks will show (1) minerals having their own form (idiomorphic); (2) minerals with their own form imperfectly developed; and (3) minerals whose form has no connection with their own constitution (allotriomorphic).

Further, even those minerals which are idiomorphic will show different outlines according to their position in the rock. The student will be able to form some idea as to the possibilities of variation in form by studying the case of a hexagonal prism like a six-sided lead pencil. A longitudinal section would show a rectangle; a transverse section, a regular hexagon; an oblique section, as a rule, an irregular hexagon; the shape varying with the degree of obliquity. Other possibilities will occur to the intelligent student.

Having indicated the number of possible cases, we must warn the student that he will not often find perfectly idiomorphic constituents. When they do occur, however, they are extremely useful as a means of identification. Much more frequently he will find minerals giving merely indications of their form. The variations in form are so numerous that it is almost impossible to give summaries in terms of crystallography; it may, however, be stated that sections of cubic crystals are rarely elongated, while many sections of crystals with lower symmetry exhibit this character.

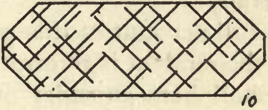
Cleavage.—Even a slight acquaintance with minerals as seen in hand specimen will be sufficient to enable the student to recall examples of minerals showing this tendency to break in definite planes. Calcite splits in three directions; in fact, it is almost impossible to break the mineral in any other direction. The common micas, muscovite and biotite, cleave in one direction with extreme facility; and gypsum also has one perfect cleavage. In thin section, these cleavages are seen as parallel straight lines. Minerals having more than one cleavage usually show more than one set of parallel cracks, those of the one set intersecting the others. The student must realise that these cleavages have a definite crystallographic orientation; in the case of the micas, the one perfect cleavage is parallel to the basal pinacoid; the three cleavage directions of calcite are parallel to the faces of a rhombohedron.

It must be understood also, that they are not necessarily parallel to faces actually present in the crystal; calcite, for example, rarely crystallises with the form of the rhombohedron to the faces of which its cleavages are parallel. The forms presented by calcite crystals are numerous and bewildering to the young student, but any one of these crystals may be cleaved in the three directions which are those of the faces of what is known as the fundamental rhombohedron. This constancy of cleavage direction for any mineral which shows cleavage at all, supplies another useful means of identification.

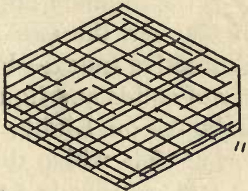
We find, however, a certain amount of variation in the different sections of any mineral. Micas, for instance, have one perfect cleavage; but in thin section we see many examples in which no cleavage is visible. The explanation is perfectly simple. Consider the analogous case of a book; the cleavage flakes of the mica correspond to the leaves of the book. Let the book rest flat on the table, and imagine it cut in vertical section; the cut surface would show a series of parallel lines produced by the intersection of the plane of section with the leaves. A horizontal section would not, however, show any cleavage, because it never cuts across a leaf. It is necessary to point out, however, that oblique sections do not always show cleavage. One might expect that, as the horizontal section already considered is the only one not cutting across the cleavages, it would be the only one not showing the cracks in section. This is not the case. If we consider a series of sections varying from the perpendicular to the parallel, we find the cracks becoming less and less conspicuous, until, long before the parallel condition is reached, the cleavages become invisible.

We have considered the case of micas in some detail as they supply a very simple case, which serves as a peg on which to hang an important principle.

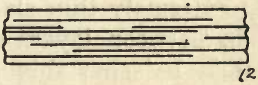
If we now pass on to the case of a mineral showing two cleavages, we have to consider, in addition to the presence of cleavage, the angle of inclination between the cleavages. Hornblende (monoclinic) is a common rock-forming mineral with two cleavage directions which are parallel to the prism faces.



10. Augite.



11. Hornblende.



12. Biotite.

A transverse section of four such faces would give a rhomb with angles of 125° and 55°; and these, therefore, are the cleavage-angles typically exhibited by this mineral in thin section. A vertical section, however, shows one cleavage-direction only; the reason should be quite clear after a little consideration. Some difficulty is encountered by many students who fail to understand the value usually attached to a cleavage angle; it is quite true that the angles formed by the intersection of the cleavages, as seen in oblique sections, would vary with the degree of obliquity if they were visible. It should be remembered, however, that if section and cleavage are not inclined at or near a right angle, the cleavage cracks will not be visible; consequently, when the two cleavages of hornblende are seen in section, that section is approximately transverse, and the characteristic angles are exhibited. Augite is another monoclinic mineral with prismatic cleavages, but here they are almost at right angles; this difference in the cleavage angles is extremely important as a means of distinction between the two minerals.

Refractive Index.—For a full account of this property of solids and liquids, the student is referred to text books on Light; we shall here consider only those aspects which directly concern us.

A rock section is an extremely thin slab of rock which is sandwiched in between layers of a substance known as Canada balsam; this sandwich rests on a glass slip and is covered by another and much thinner slip of glass, but these may be ignored. We are concerned here only with the substance in contact with the minerals making up the rock.

It is well known that colourless transparent substances are visible only when they differ in optical density (refractive index) from the fluid in which they are immersed; and the greater the difference between the two substances, the more conspicuous will be their limiting surfaces. An instructive experiment is to powder common glass and drop it in water. Better still, powder a fragment of the mineral cryolite and drop the powder in water; it is with the greatest difficulty that the mineral can be seen when immersed in the liquid, and one is inclined to believe that it has passed into solution. It is invisible, however, merely because the two substances, cryolite and water, have almost exactly the same refractive index.

We are now in a position to make a general statement. A transparent solid is more or less visible according to whether it is more or less different in refractive index from the fluid in which it is immersed. The minerals in thin section may be considered to be immersed in a liquid—the Canada balsam. On examining the margins of the transparent minerals in section, we find, by working round the edges of the section where the minerals are in contact with Canada balsam, that some of the edges stand out conspicuously, while where other minerals come in contact with Canada balsam, the junction is comparatively inconspicuous. The minerals are in contact with the mounting medium also on their upper and lower surfaces, and these supply us with additional information. In consequence of the method of preparation of thin sections, these surfaces are rough; they are grooved and pitted by the powders employed in the grinding. Those minerals differing in refractive index from that of the mounting medium show these rough surfaces when carefully focussed; on the other hand, those constituents approximating in refractive index to the Canada balsam always appear to be smooth in consequence of this approximation. Clearly, then, we have here a means of determining by mere inspection whether or not a particular mineral has a refractive index which is near to or distant from that of Canada balsam, 1·54.

But it is necessary to determine whether the refractive index of the mineral in question is higher or lower than that of Canada balsam; and a means of making this determination is supplied by BECKE'S TEST. Using the high power objective, focus carefully an edge of the mineral where it is in contact with the mounting medium, choosing an edge which is as clean as possible; if a small fragment of the mineral has become detached from the rest of the rock and thus lies surrounded by Canada balsam, it will supply the ideal conditions. Rack the tube up and down a little on each side of the position of focus, being careful not to push the objective through the slide, an accident which occasionally happens to the beginner. It will be seen that, when the fragment is slightly out of focus, it is surrounded by, or encloses, a ring of light, which expands or contracts as the tube is alternately raised and lowered.

There are two cases. The refractive index of the mineral is (1) higher, and (2) lower, than that of Canada balsam, 1·54. It is convenient to consider only what happens when the objective is being raised. In the first case, when the mineral is denser than the mounting medium, the ring of light will contract; it will pass from the Canada balsam to the mineral. When the mineral is the less dense substance, the light passes from the mineral to the balsam.

In both cases, as the objective is raised, the light passes from the substance with the lower, to that with the higher refractive index. It is thus possible, by this test, to eliminate all those minerals which differ from the one under consideration in being higher or lower than Canada balsam in refractive index; and the method of elimination will sometimes be found extremely useful in making identifications. A concave mirror should always be used in making this test, and a diaphragm will be found useful in difficult cases. The existence of this more intense illumination depends on the property of total internal reflection, as the light impinges on a surface limiting a dense substance. In some cases it is possible by this method to compare the refractive indices of two minerals in contact, but the contact is not always sufficiently good to give results.

As examples of case 1, topaz, apatite, or olivine gives good results. Fluor, nosean, and leucite supply good examples of case 2.

When reference is made to "the refractive index" of a doubly refracting mineral, it must be understood that the mean refractive index is referred to, also, that that value has been obtained when using sodium light.

Alteration.—Orthoclase felspar supplies us with a good example of a mineral which is liable to decomposition on exposure to atmospheric conditions. If the rock from which the section has been cut is "fresh," this mineral is quite colourless and transparent; but when decomposed it has lost its transparency, and has become a mere aggregate of countless greyish semi-opaque particles of the hydrated mineral, kaolin. Some fragments are in an intermediate condition—altered merely in parts; the student should examine slides containing the mineral showing different degrees of alteration. The case of orthoclase is specially important because the tendency to decomposition is often useful in distinguishing this mineral from quartz, which it may strongly resemble.

Olivine, also, is unstable under atmospheric conditions, and is frequently seen more or less altered to the green mineral serpentine. The mode of alteration is very characteristic. Olivine, when fresh, is a colourless mineral, usually traversed by irregular cracks, and it is along these that the alteration product first developes. Later stages show that these "channels" of serpentine have become wider, the "islands" of fresh olivine have become smaller, and the last stage shows the mass of serpentine having the form of the olivine from which it was derived. The serpentine is commonly associated with granules of black iron oxide, another product of the decomposition of the original olivine.

Biotite is another unstable mineral, the product in this case being the green mineral chlorite. Excellent examples showing different stages of alteration are obtainable in different sections, ranging from the fresh brown biotite to the pseudomorph in chlorite.

Inclusions.—In some few cases, minerals may be seen to contain inclusions of other substances which are useful in making identification. The best examples are seen in some specimens of leucite, which may show small fragments of other minerals (notably green augite) arranged in a ring. The student, however, must not expect all specimens of leucite to exhibit this character.

Other minerals contain inclusions, but the character is not often of service in distinguishing the mineral. Quartz may show liquid and gas inclusions, and orthoclase sometimes contains glass.

Zoning.—It is often found that a crystal is not uniformly coloured, but exhibits an arrangement of colour bands which are concentric with the exterior. Nosean, for example, is commonly distinguished by a well-marked brown periphery, although the centre is colourless. Tourmaline, brown garnets, and pyroxenes frequently show a succession of concentric rings of colour; this variety of zoning is known as colour-zoning. A similar structure, already mentioned under the heading of inclusions, is exhibited by some minerals in consequence of their manner of arranging inclusions. Leucite is the most striking example; but a less conspicuous zoning by inclusions is sometimes seen in felspars and pyroxenes.

Zoning is most commonly exhibited by the minerals which are grouped together as isomorphous, and no better example can be found than the Albite-Anorthite series of plagioclase felspars. It is often found that the crystal is not homogenous, but is built up of successive shells, each of which has a composition which is different from that of its neighbours; the crystal has commenced its growth as one member of the series, but has received additions of ever-varying composition. In consequence of this structure, the mineral being liable to decomposition and the several shells being unstable in different degrees, the weathering action has picked out the less stable layers and has emphasized the zonal nature. When the kaolinised layers have received a stain of iron oxide, as sometimes happens, the zoning becomes still more striking. But even when the felspar is quite fresh, the zones are sometimes visible in consequence of the difference in refractive index between them. The colour-zoning of tourmaline, pyroxenes and garnets, is also to be attributed to an isomorphous relationship; it happens to be the case that the different members of the particular series are differently coloured.

CHARACTERS OF MINERALS IN REFLECTED LIGHT

HITHERTO we have considered only the case of minerals which, in section, transmit a certain amount of light; but some minerals, even in thin section, are quite opaque, and a special method of investigation is employed for their identification. The mirror must be tilted so that no light comes from below, the tube placed vertically, and the examination should be conducted near a window or other source of light, so as to allow of reflection from the upper surface of the slide. In these circumstances, magnetite shows a black metallic surface if fresh; it is associated with a red alteration product (hæmatite) if decomposed. Ilmenite (titanoferrite) if fresh, has also a black metallic appearance, but decomposition results in the formation of a whitish substance (leucoxene) which may be arranged in triangular areas; but this geometrical arrangement is not always seen. Iron pyrites shows a brass-yellow colour and metallic lustre.

This test may also be employed with advantage in the examination of some minerals which are not opaque; the distinction between quartz and felspar may sometimes be made advantageously by observing the mineral in question in reflected light. Any alteration of the felspar is easily seen by this method.

It should be remembered that in all the methods of examination to be described later, transmitted light is to be used.

CHARACTERS OF MINERALS WITH THE LOWER NICOL INSERTED

HAVING completed a survey of the characters employed in mineral identification when the microscope is used without either nicol, the attention of the student may be directed to the characters to be observed when the lower nicol (the polariser) is in position in the axis of the instrument, the upper nicol (the analyser) still being swung aside, as in the preceding section.

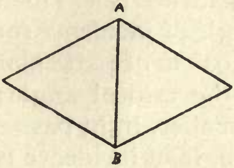
The Nature of Light.—In order to understand the phenomena, it is necessary first to realise some elementary facts as to the nature of light and the construction of the Nicol's prism.

As light may be transmitted through what is known as a vacuum, it is necessary to assume the existence of a substance pervading all space, by means of which the transmission is effected. This substance is known as the ether. It is quite certain that light is transmitted as a consequence of a series of vibrations which take place at right angles to the direction in which light is travelling, and the theory formerly accepted was that the ether particles themselves performed these vibrations to and fro without undergoing any movement along the line of propagation of the ray. The theory has now been considerably modified, and a theory of oscillation, not of the particles themselves, but of their electrical condition, is now held to account for the facts more satisfactorily. But these oscillations or vibrations certainly do take place, and they take place at right angles to the direction of propagation of the light. A ray of ordinary light performs its vibrations in all directions possible subject to this limitation, that is, in all the directions perpendicular to the direction of transmission; but light which has passed through a nicol performs all its vibrations, not merely perpendicular to this direction, but parallel to a definite line which fulfils this condition. Such light, performing its vibrations in one plane only, is said to be polarised, and we have now to learn something about the construction of a "nicol" in order that we may realise the conditions of investigation.

The Double Refraction of Calcite.—The nicol is made of a clear variety of calcite known as Iceland Spar, a substance possessing to a remarkable degree the power of splitting a ray of entering light into two—the property we know as double refraction. The mineral has an extremely good cleavage in three directions, and, split along these cleavages, it yields a fragment of the form known as the rhombohedron. Light entering such a fragment perpendicularly to one of the cleavage planes is split into two rays, and, in consequence, any object viewed along such a perpendicular is doubled; two images reach the eye. The most satisfactory demonstration of this fact is obtained by resting the fragment on a sheet of white paper on which a small blot of black ink has been made. Seen from above, such a spot is doubled. Now rotate the fragment. It is seen that one of the images remains stationary, while the path of the other is the circumference of a circle with the stationary image as centre. The stationary image behaves just as if the crystal were a slab of glass; it is therefore said to be produced by the ordinary ray. The ray producing the movable image, on the other hand, does not obey the ordinary laws of refraction. To anyone who has studied only singly refracting substances, its behaviour appears to be quite extraordinary, and it is therefore known as the extraordinary ray.

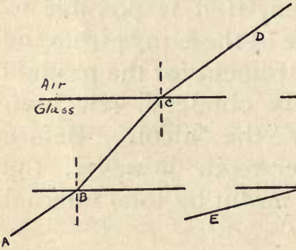
By looking at the surface obliquely, we can see that the ordinary image appears to occupy a higher position inside the fragment than does the extraordinary image. In other words, the density of the crystal for the ordinary ray is greater than for the extraordinary ray, or, the velocity of the extraordinary ray is greater than that of the ordinary ray. The fact that two such rays travelling in a doubly refracting crystal have different velocities, is extremely important to the student who wishes to understand what follows, and this experimental demonstration of the fact should help materially to fix the ideas.

We have seen, then, that a ray of light incident normally on a face of such a rhombohedron is split into two, each ray having its own path and a velocity which depends on the nature of the crystal. Still further information may be obtained if the two spots are examined through a nicol. The nicol may, for the present, be considered as an instrument capable of transmitting only that light which vibrates in a direction known as the principal section—the line A.B. (Fig. 13). When the nicol is rotated on a vertical axis, it is seen that the two spots appear and disappear alternately, and that a rotation of 90° is necessary to produce this alternation. Granting our assumption as to the direction of the vibrations transmitted by the nicol, it is easily demonstrated that each ray emerging from the cleavage fragment is polarised (performs its vibrations parallel to one line only), and that the two vibration directions, that of the ordinary ray and that of the extraordinary ray, are at right angles. Clearly, then, if it is possible to prevent the emergence of one of these rays from the Iceland spar, an efficient instrument for the production of polarised light may be obtained. Such an elimination is effected by the nicol. Before its operation can be understood, however, the student must realise what is meant by total internal reflection.

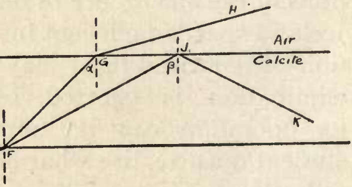


13. The nicol seen from above.

The Nicol.—A ray of light passing obliquely from one transparent substance to another, is refracted at the surface, the amount of refraction being proportional to the difference in optical density between the two substances. A ray passing from the less dense to the more dense substance is refracted towards the normal. Now, consider what happens when a ray meets the surface from the more dense side, taking the case of glass and air. A ray such as B. C. D. (Fig. 14) passes from one substance to the other, but is refracted away from the normal—the angle of incidence is less than the angle of refraction. The angle of incidence for which the angle of refraction is 90° is of particular importance, and is known as the critical angle; when the angle of incidence is smaller, light passes to the rarer medium; when the angle of incidence is greater, no light emerges; it is reflected from the surface back into the denser medium. If then, two rays impinge on such a surface, with angles of incidence less and greater than the critical angle, one will pass to the rarer medium, the other will be totally reflected at the surface. The one succeeds in passing the surface, the other fails.



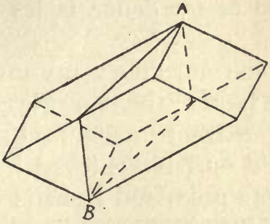
14. Refraction.



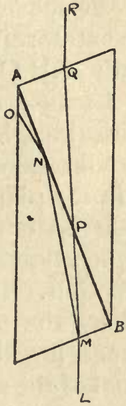
15. Refraction and total reflection.

Figure 15 represents the case of a doubly refracting substance where the entering ray, E. F., divides; one ray, E. F. G. H., emerges, because α is less than the critical angle; another ray, E. F. J. K., is totally reflected at J., because β is greater than the critical angle.

The student is now in a position to understand the principles on which a nicol is constructed.



16. The film of Canada balsam within the nicol.



17. Separation of the two rays by the nicol.

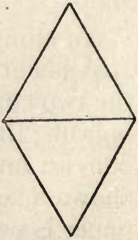
An elongated cleavage rhombohedron of Iceland spar is cut into halves, as shown in Figure 16, and the two cut surfaces cemented together with Canada balsam; the two end faces are ground down so as to convert an angle of 71° to one of 68°. Figure 17 shows a section of the nicol where the plane of the paper is perpendicular to the film of Canada balsam A. B. with the vertical edges parallel to the axis of rotation when in position in the microscope. A ray of light entering at the lower surface is split into two. The ordinary ray is the more refracted, meets the film of balsam at N. with an angle of incidence greater than the critical angle, and is consequently totally reflected to O, as the refractive index of the calcite for the ordinary ray is greater than that of the balsam (1·54). None of its light emerges at the upper surface of the nicol.

The extraordinary ray is less refracted, and takes the path M.P.Q.R., penetrating the film of balsam at P., because the angle of incidence is less than the critical angle.

The vibrations of the extraordinary ray are executed in the plane of the paper; the emerging light is made up entirely of extraordinary rays; and, consequently, the desired end is achieved by this construction. Only plane polarised light is transmitted by the nicol. The vibration direction of this emerging light is the direction of the shorter diagonal of the end face as seen from above.

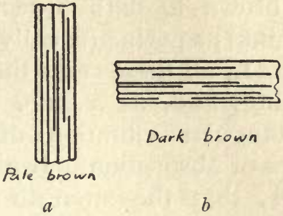
Pleochroism.—We are now in a position to consider the microscopic examination of thin sections when the lower nicol, the polariser, is in position in the axis of the instrument underneath the stage.

The light reaching the section has previously passed through the polariser, and is consequently performing its vibrations parallel to the principal section of that nicol, which, although the nicol is capable of rotation, we shall, for purposes of description, consider to be fixed in an E.W. direction. If now a section containing the mineral biotite is placed on the stage, and the stage rotated, it will be seen that the mineral changes colour from a pale brown to a dark brown,



18. Plan of the polariser in position.

and that a rotation of 90° is necessary in order to produce the maximum change.



19. The pleochroism of biotite.

This property of certain minerals, exhibited very strikingly by biotite, of changing colour when thus examined, is known as pleochroism. It supplies us with an extremely valuable means of distinguishing many minerals with the polarising microscope.

The case of biotite will be easily understood if it is remembered that such a section is capable of transmitting light vibrations in two directions only. These two directions are at right angles, parallel and perpendicular to the cleavage direction. In position (a) Fig. 19, the whole of the light transmitted vibrates in one of these directions, and the mineral absorbs its minimum amount of light. In position (b), the whole of the light transmitted vibrates in the other of these directions, and the mineral absorbs its maximum amount of light. In an intermediate position, some light is transmitted vibrating in each of the two vibration directions, each direction absorbs its own amount of light, and consequently the transmitted light is intermediate in shade between the two pleochroism extremes.

Other common minerals affording good examples of pleochroism are, hornblende (pale green to dark green or pale brown to dark brown); tourmaline (usually pale brown to dark brown); andalusite (colourless to pink); ægerine (usually a rich yellow to blue green). In all these cases the minerals are doubly refracting, and, as a rule, their sections have two rectangular vibration directions with different powers of absorption. It must be understood, however, that the strength of the pleochroism depends on the direction in which the section is cut; for instance, basal sections of biotite exhibit very feeble pleochroism, while basal sections of tourmaline are absolutely non-pleochroic. This crystallographic variation emphasizes the necessity for examining as many fragments of the mineral as are available in the slide before an identification is made.

Pleochroic Haloes.—Certain minerals, otherwise colourless in thin section, show curious circular brown areas, each of which contains at its centre an included fragment of some other mineral. These brown patches change colour when the section is rotated above the polariser; they are, in fact, pleochroic areas in an otherwise colourless section. It is quite certain that the including mineral has acquired this property in consequence of the presence of this minute inclusion. Several theories have been put forward to account for these pleochroic haloes, but it has now been satisfactorily proved that the development of colour around the inclusion is the result of the fact that such an inclusion is radio-active, and that its ejected particles have produced an ionisation effect on the mineral in contact. Minerals showing these haloes are muscovite, cordierite, tourmaline, and biotite. The last two minerals are not colourless, even in thin section, but in their case the colour has been rendered more intense around the inclusion.

Twinkling.—A change which cannot be called pleochroism takes place when sections of the mineral calcite are rotated over the polariser. Calcite is doubly refracting, and, consequently, most of its sections possess the two rectangular vibration directions for transmitted light. When the rotation takes place, the mineral shows, at one time, rough surface, well defined borders, and conspicuous cleavages; at another time, smooth surface, faintly defined borders, and inconspicuous cleavages. The change is from a mineral with a high refractive index to one with a low refractive index, and these extremes of relief are exhibited when the two vibration directions of the calcite in section come to be parallel in turn with the vibration direction of the light emerging from the polariser. This means that each of the two vibration directions has its own refractive index. A rapid rotation of the stage (or of the polariser beneath it) produces a rapid change of relief which cannot be better described than by the name of twinkling. This is quite different from pleochroism, which is essentially a change of colour, whereas the calcite remains quite colourless. Other minerals with a high double refraction show the same effect, notably the other rhombohedral carbonates, but few other minerals show a conspicuous change of relief, though theoretically, all doubly refracting sections ought to show some such change. Only in a few cases, however, such as the one cited, is the change sufficiently great to be worthy of consideration in practice.

Crystallographic Summary.—It is a matter of some difficulty to tabulate the pleochroic properties of minerals crystallographically in such a way as to be of assistance to the student, but it may be stated quite definitely that the following sections are non-pleochroic:—

All colourless sections.
All sections of cubic minerals.
Basal sections of dimetric minerals.

Other sections may show pleochroism. Some show a striking change of colour, others merely a slight change; in still others the absorptive powers of the mineral for the two vibration directions are so nearly equal that even the most imaginative observer fails to notice any change of shade or colour.

CHARACTERS OF MINERALS BETWEEN CROSSED NICOLS

WHEN minerals are to be examined between crossed nicols, both analyser and polariser must be placed in the axis of the microscope, and, moreover, the two nicols must be rotated to such positions that, with an empty stage, no light reaches the eye. In order to simplify this adjustment each nicol is provided with a catch which indicates the correct position. It must be borne in mind by the beginner that if the two nicols are used, they *must* be in the crossed position, and neither may be rotated; rotation of the stage, however, is not only permissible, but essential. We have already seen that the light transmitted by the polariser vibrates only parallel to an E.W. line—the principal section. The analyser is similar to the polariser in all respects except that of position; its principal section is in a N.S. direction. The result of this "crossing" of the two nicols is that the emerging extraordinary ray of the polariser becomes the ordinary ray of the analyser, and is totally reflected from the film of balsam. With an empty stage, the polarised light from the lower nicol is allowed a free passage to the upper nicol, and, consequently, the whole of the light transmitted by the lower is stopped by the upper; the field is quite dark.

A plate of glass, or any other singly refracting substance placed upon the stage does not produce any alteration of this condition, the reason being that it has no power to change the vibration direction of the entering light. Canada balsam is another singly refracting substance, hence, we are quite certain that if any alteration is produced in the dark field when a microscope slide is placed on the stage, such alteration is due entirely to the minerals in the slide.

Isotropism and Anisotropism.—Some mineral sections have no power to produce any illumination; they are singly refracting and consequently are quite dark between crossed nicols. They remain in that condition during a complete rotation of the stage, and are said to be ISOTROPIC. All sections of minerals crystallising in the cubic system, and basal sections of minerals crystallising in either of the dimetric systems, are isotropic. All other sections are ANISOTROPIC, that is, they are alternately dark and illuminated when the stage is rotated.

Extinction.—It is found that anisotropic sections, for most positions of the stage, transmit light of a certain colour, but that, from time to time during rotation they become dark—they are said to extinguish; and if the angle of rotation is taken, it will be found that extinction takes place at intervals of 90° exactly. For instance, most sections of the mineral apatite (crystallising in the hexagonal system), which are elongated, colourless, have a high refractive index, and a basal cleavage, when rotated between crossed nicols, show a colour which is grey; this is extinguished when the edges are N.S. or E.W. Another good example is supplied by the mineral muscovite. This usually shows no definite outline, but seen in ordinary light it is colourless, and shows a well-defined cleavage. The colour between crossed nicols is bright pink or green, and this extinguishes when the cleavage is N.S. or E.W. Both these cases show straight extinction, that is, extinction takes place when some definite direction, edge or cleavage, is placed N.S. or E.W.

Other minerals, however, although they extinguish at intervals of 90°, do not extinguish in these positions, but at some other position during rotation. Most sections of the mineral augite, for instance (pale brown, high refractive index, and showing one or two good cleavages) extinguish when the edges of the fragment are not parallel to either of the rectangular cross-wires in the eye-piece of the microscope—placed N.S. and E.W. Such sections show oblique extinction, and it is sometimes useful to know the position at which extinction does take place. This angle of extinction is measured either from the N.S. or the E.W. cross-wire. In order to determine its value, the stage is first rotated until the mineral fragment is extinguished, when the angular position of the stage is read; the stage is then rotated until the crystal edge is parallel to one of the cross-wires, when the stage reading is again taken; the difference between the two readings gives the angle of extinction. It will be seen, however, that this is only one of two possible values; the other value would have been obtained if rotation had brought the edge parallel to the other cross-wire. These two values are, of course, complementary, and it is usual to take the smaller value as the angle of extinction.

Polarisation Colours.—We may now proceed to consider the reasons why a section in one position gives a polarisation colour, and in another becomes extinguished. It has already been seen (1) that if light leaves the section vibrating as it entered (as it left the polariser) it must suffer elimination in the analyser; (2) that a doubly refracting section has two rectangular vibration directions which are the only possible directions of vibration in the section; (3) that extinction takes place at intervals of 90°.

If we suppose that the mineral section is in such a position on the stage that its two vibration directions coincide with the cross-wires, N.S. and E.W., the light emerging from the polariser will travel through the section vibrating exclusively along the E.W. vibration direction in the section, and will emerge from it still vibrating E.W., that is, in such a way as to be totally reflected by the analyser. A similar result must be obtained if the section is turned through 90°, for then the other vibration direction has come to lie E.W., and again total reflection is effected by the analyser. Such positions of the section, then, must secure extinction.

The reason for the production of polarisation colour when the vibration directions are not parallel to the cross-wires, is not quite so simple; but it is not very difficult to obtain some idea as to the causes. It must be realised that the two vibration directions in the section are the only two possible for light penetrating the mineral, and also that while each vibration direction secures retardation of the light, the light which has vibrated in one of these directions has suffered a retardation which is not equal to that suffered by the other. Suppose that these directions make angles of 45° with the cross-wires. The light emerging from the polariser is vibrating E.W. On entering the section it divides; some vibrates N.E : S.W., the remainder N.W : S.E. The two rays travel up to the analyser, and although there must be some resolution of the two into N.S. and E.W. vibrations, the remainder reaches the analyser vibrating in other directions. The essential point is that this light has traversed the section vibrating in different directions, and consequently there is a relative retardation. On entering the analyser, the vibration directions are reduced to two only: E.W. and N.S. The E.W. vibrations are totally reflected from the the film of balsam, and it only remains to consider the N.S. vibrations. Some portion of the light has traversed the section vibrating N.E : S.W., the remainder has traversed the section vibrating N.W : S.E. That is, there are two rays vibrating in the same plane with a difference of phase, and this difference is comparable with the wave lengths of light. Clearly then, the conditions are such as to produce interference, for it is evident that for at least one of the constituents of white light, the half wave length must divide into the relative retardation so as to give some odd whole number. Disregarding other kinds of interference, this particular kind must result in the elimination of the colour in question; the complementary colour (the polarisation colour) penetrates the analyser, and reaches the eye. The student will see that the polarisation colour depends entirely on the amount of the relative retardation effected between the two rays traversing the mineral section; this is quite unlike the case of pleochroism, which depends on the difference between the absorptive powers of the two vibration directions.

In considering the difference between the two retardations, it is necessary to take into account:—

I. Thickness of section.
II. Crystallographic orientation of section.
III. Nature of mineral.

I. That the polarisation colour is dependent on the thickness of section in the case of anisotropic minerals, is beautifully demonstrated when a wedge-shaped fragment is placed between crossed nicols. Crystalline gypsum* is a suitable material for experiment. This mineral, which possesses a perfect clinopinacoidal cleavage, should be cleaved into a flake about one sixteenth of an inch in thickness, and from this a small rectangle measuring about 1in. × ¼in. should be cut with a knife, care being taken that the edges of the rectangle are paralled to the two vibration directions. This can be

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* Quartz is equally useful.

done by drawing an E.W. or N.S. line on the flake when it is in extinction between crossed nicols. The rectangle should be cemented with Canada balsam near the end of a glass slip, half an inch in width, and carefully ground down so as to make one end as thin as possible, while retaining the full thickness at the other. When such a wedge is mounted and placed between crossed nicols in a N.E : S.W. or a N.W. : S.E. position, it is seen to exhibit the succession of gorgeous colour-bands known as Newton's Scale. Every student should take an early opportunity of examining this scale,* as no amount of description will serve to give an adequate idea as to the nature of the colours. It will be necessary to refer repeatedly to this scale, but for the present we may look upon it simply as a complete proof that the particular polarisation colour produced depends on the thickness of the doubly refracting mineral through which the light has passed, the greater thickness effecting a greater relative retardation.

II. That equal thicknesses of the same doubly refracting mineral produce different polarisation colours when the sections have different crystallographic orientations, may be easily proved with almost any such mineral. Quartz supplies a very suitable case. If three sections are cut, say, parallel to the basal pinacoid, the rhombohedron, and the prism, ground down to the ordinary thickness, and mounted, they will show quite different colours between crossed nicols; the basal section is

* See frontispiece.

isotropic, the other two are anisotropic; the rhombohedral section polarising in grey, and the prismatic section in yellow. Barytes is another common mineral giving good results; the macropinacoidal section polarises in yellow, and the brachypinacoidal section in bright pink or green.

III. That the polarisation colour depends on the nature of the mineral may be demonstrated by mounting prismatic sections of quartz and calcite side by side. The quartz polarises in yellow, and the calcite in pale grey.

Birefringence.—All these polarisation colours in the case of anisotropic sections are due to the amount of relative retardation effected in the section—the difference between the velocities of the two rays travelling in the section, or, expressed differently, the difference between the two refractive indices, the retardation increasing, of course, with increase of thickness. Taking quartz as an example, we have seen that differently oriented sections produce different polarisation colours; if these colours are compared with those of Newton's scale, it will be seen that all three colours are found near the thin end of the wedge—low down in the scale; the yellow is the highest of the three, and this colour must be produced by that section of the mineral for which the difference of refractive indices is greatest. No other section of quartz will show polarisation colours higher in the scale than the yellow produced by the prismatic section; that is, such a section contains the two vibration directions having the maximum velocity difference for the mineral. This difference is best expressed numerically as a difference between the two refractive indices.

It may be demonstrated experimentally that when the light vibrates parallel to the *c* crystallographic axis of quartz, the refractive index is 1.553, and that when the vibrations take place at right angles to this direction, the refractive index is 1.544. The difference, .009, is clearly a measure of the strength of the double refraction for this particular mineral, and this value is the birefringence.

Every doubly refracting mineral agrees with quartz in this respect, that it has one particular section containing the two vibration directions giving the maximum and minimum velocities for the mineral. Light vibrating in these directions has the maximum difference of refractive index for the mineral; the difference is the birefringence of that mineral, and, stated numerically, gives us some idea as to what polarisation colours the section of ordinary thickness is capable of producing.

Newton's Scale.—As it is often convenient to refer to these colours in terms of Newton's scale, it is necessary to examine this more closely. Examining these colours, beginning at the thin end of the wedge, we see that the first few colours are, dark grey, light grey, white, yellow, and red; these constitute what is known as the first order. The succeeding colours include at intervals, bands of red or pink, the pink becoming paler and paler until it is indistinguishable from pale grey or white. These repeated bands supply a useful means of splitting up the scale into orders, each band terminating an order. It is difficult to state how many orders are exhibited by such a wedge, as, to some eyes, a colour high up in the scale may appear to be pink or green, while to others it is simply a white or grey. However, seven of these orders are distinctly visible; higher colours may be referred to as whites of a high order. No two orders exhibit quite the same colours, but only practice will enable the student to state definitely on examining mineral fragments between crossed nicols, to what order exactly the colour belongs. The first order colours are fairly characteristic; those of the second and third orders are the brightest in the scale; those of the higher orders become more and more pale. It is well for the student to realise that it is not advisable to use the words high and bright as synonyms; the higher colours in the scale are not bright.

An anisotropic section, colourless in ordinary light, shows when between crossed nicols a colour which is due entirely to interference; but the case of an anisotropic mineral section which absorbs some constituent of white light is not quite so simple. Muscovite, which is colourless in ordinary light, polarises in bright pinks and greens; biotite, with approximately the same birefringence, usually shows only a greyish brown. The reason for this is, of course, that biotite shows interference colour and absorption colour simultaneously. Tourmaline and brown hornblende supply other examples of this masking of the polarisation colour; while brown sphene, whose polarisation colour is a high order grey, shows between crossed nicols a colour not noticeably different from the absorption colour. One can only say of such a section of sphene, that it is anisotropic.

A few minerals, placed between crossed nicols, show what are known as ultra-polarisation colours. These colours are not to be found in Newton's scale, and are shown only by a few minerals, all with a very low birefringence. Chlorite, a monoclinic micaceous mineral, and zoisite, an orthorhombic mineral allied to epidote, occasionally show these ultra-blues or ultra-browns. The most satisfactory explanation of these polarisation colours, is that the section is isotropic for some colours and anisotropic for others.

Twinning.—The observant student has already noticed that while some mineral sections polarise and extinguish as a whole, differences of colour being easily explainable as the result of variations in thickness, some particular mineral fragment is divided into two areas, the dividing line being straight, and usually sharply defined. Of these two areas, one is in a position of extinction when the other is illuminated, and vice versa. Moreover, the polarisation colours of the two areas are unlike. Orthoclase felspar will often show this difference of extinction position and also of polarisation colour, one area showing yellow and the other grey. These peculiarities are indicative of twinning, and often afford a useful means of distinction between different minerals. The reason for the different positions of extinction of the two areas is to be found in the fact that, as they have different crystallographic orientations, their rectangular vibration directions are not parallel, each to each. The reason for the difference of polarisation colour is to be found also in the fact that the two areas have different crystallographic orientations; they behave just as if they were two separate sections of the same mineral. This particular kind of twinning, resulting in the production of two such areas only, is known as simple twinning.

Another type of twinning is shown by sections of plagioclase felspars such as labradorite. In this case, there are not merely two such areas, but any number from three upwards in one crystal. When one of these fragments is examined between crossed nicols, it shows alternating black and illuminated ribbons when one set is in extinction. It is worth noting that alternate ribbons extinguish simultaneously. This particular type of twinning, of which labradorite has been taken as an example, is known as lamellar twinning.

The fact that twinning is exhibited commonly by some minerals and never in others, renders this particular character very useful in mineral identification. Simple twinning serves to distinguish orthoclase felspar from quartz, and from plagioclase felspar—which shows lamellar twinning.

It is obvious that this test of twinning, the different positions of extinction, can only be observed in the case of anisotropic sections. This particular kind of evidence is not available in the case of minerals crystallising in the cubic system, and it is therefore a matter of some difficulty to prove the presence of twinning in sections of minerals having such a high degree of symmetry. Some indication, however, is sometimes given by a re-entrant angle, though this is not a satisfactory proof of twinning.

Zoning.—The zoning of such crystals as those belonging to the Albite-Anorthite series has already been mentioned, and it has been pointed out that this particular character may be observed in ordinary light in consequence of the fact that the different shells have unequal refractive indices and possibly different degrees of alteration. But this zoning is often quite inconspicuous until the examination is made between crossed nicols. As each zone has its own position of extinction, the structure is still more conspicuous in this condition of the microscope, notwithstanding the fact that the same crystal may show lamellar twinning. Pyroxenes also may exhibit zoning between crossed nicols, even in cases where such a character was invisible in ordinary light.

Anomalous Double Refraction.—It has been seen that all sections of minerals crystallising in the cubic system, ought, when examined between crossed nicols, to be isotropic; but many sections of the mineral leucite (usually considered to crystallise in this system) show grey polarisation colours in intersecting ribbons.

The "anomaly" is that a cubic mineral is anisotropic, and that anomaly is bound to exist as long as we regard the mineral as belonging to this system. The mineral is not really a cubic mineral, but its crystals have a symmetry which is so nearly that of the trapezohedron, that it is a matter of some difficulty to place it elsewhere. Some sections of garnet exhibit similar anomalies.

Aggregate Polarisation.—This phenomenon of aggregate polarisation is seen in those cases where a mineral has been decomposed with the production of an aggregate of smaller, anisotropic fragments of some other mineral or minerals. The alteration product is made up of small fragments with all possible orientations, and consequently there is never complete extinction of the pseudomorph—a fact which occasionally troubles students. If such a pseudomorph be looked upon as a crowd of small individuals, the difficulty disappears.

Determination of Polarisation Colour.—Up to the present we have used the wedge merely to demonstrate the effects of variation in thickness of an anisotropic section. We have now to consider some other uses to which it may be put.

It has been suggested that, by practice, the student may acquire the ability to recognise the particular order in which any mineral fragment is polarising, merely by inspection; but the wedge may be used to place the matter beyond doubt. In order to demonstrate the method, a fairly large fragment of a doubly refracting mineral in thin section should be placed between crossed nicols, and the stage rotated until it occupies one of the positions where the polarisation colour is at its brightest; the mounted wedge should then be inserted into the slot of the eye-piece until it occupies a position immediately above the fragment to be examined. In such circumstances the polarisation effect is due partly to the mineral on the stage, and partly to the wedge in the slot. There are two possible cases:—

(1) The effect of the two is as the sum of two quantities having the same sign — the polarisation colours of the two are higher in the scale than either alone.

(2) The effect of the two is as the sum of two quantities having unlike signs — the polarisation colours of the two are lower in the scale than either alone.

It is the second case that we require; a rotation of the stage through 90° will convert case (1) into case (2). Having obtained the required opposition between section and wedge, it will be seen that at some position in the latter, a black band takes the place of one of the colour-bands in the scale; the particular band of colour replaced by this compensation band is the polarisation colour of the mineral plate. If the mineral plate whose polarisation colour we set out to determine is the only fragment in the slide, or if it is at the edge of a rock section, the fact may be demonstrated by placing the section in such a position that it is only covered by one side of the wedge. On this side, the compensation band will be obtained; on the other, the ordinary scale will be exhibited; and the compensation band will be continuous across the wedge with the colour which is that exhibited by the section alone.

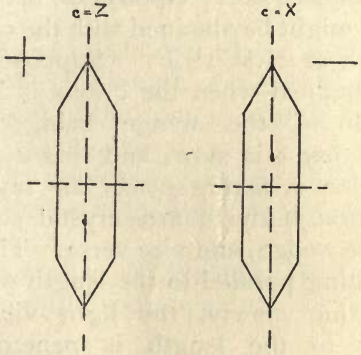
The test may be applied to any anisotropic section, though in the case of a small fragment, or one of irregular thickness, a little care is necessary in making the determination.

Sign of Dimetric Minerals.—We have already seen that a section of quartz cut parallel to the principal crystallographic axis *c*, polarised in yellow of the first order, the highest polarisation colour possible in sections of quartz of the standard thickness. All minerals crystallising in the hexagonal and tetragonal systems (dimetric) are similar in this respect, that, although the highest possible polarisation colour for any mineral is a function of the birefringence, they all exhibit their highest polarisation colour when cut in such a direction that the crystallographic axis *c* lies in the plane of section. This means that, for such a section, the difference in velocity of the two rays penetrating it, is at its maximum; and as such sections show straight extinction, the two vibration directions are respectively parallel to and perpendicular to the length of the crystal. These particular directions, being the vibration directions of the rays with the two extremes of velocity for the crystal, are known as ether axes; that of the fastest ray is referred to as the X ether axis, and that of the slowest ray as the Z ether axis.

There are two cases:—

Where *c* coincides with Z, the double refraction is positive.

Where *c* coincides with X, the double refraction is negative.



Dimetric crystals.

20. Positive. 21. Negative.

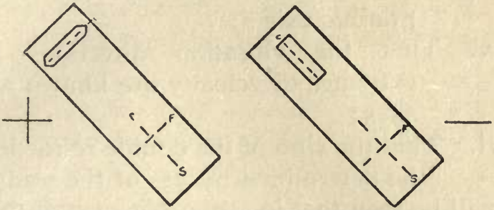
The wedge may be used to determine which of these two cases a particular vertical section of a dimetric mineral represents.

Before this can be done, however, it is necessary to learn something more about the wedge. We know that its two vibration directions are respectively parallel and perpendicular to the length, but we have not yet determined which of these is "fast" and which "slow." In order to make this determination, we require a vertical section of a dimetric mineral whose sign is known. A small crystal of quartz meets our requirements admirably; it is well-known that quartz is positive, therefore in a vertical section the length is the direction of slow vibration.

The section is placed on the stage between crossed nicols and brought to a position of maximum illumination, and the wedge inserted into the eye-piece slot. Opposition between crystal and wedge might be obtained with the crystal either N.E : S.W., or N.W : S.E. Suppose that opposition is obtained when the *c* axis is N.E : S.W., the length of the wedge being N.W : S.E. We know that *c* is slow, and that *a* is fast, and as opposition is taking place, the ray that came quickly through the quartz crystal comes slowly through the wedge, and vice versa. Therefore, the light vibrating parallel to the length of the wedge is penetrating slowly, the light vibrating perpendicular to the length is penetrating more rapidly.

We have thus determined the character of our wedge, and can speak of it as a slow wedge in terms of the kind of ray vibrating longitudinally. This fact having been determined, the knowledge thus obtained may be applied in order to determine the sign of any vertical section of a dimetric mineral.

Apatite, for instance, is elongated along the axis *c*. A section parallel to *c*, tested with the wedge between crossed nicols, is seen to give compensation with its length N.W : S.E.



Positions of crystals giving compensation with the slow wedge.
22. Positive. 23. Negative.

As wedge and crystal must be in opposition, and as we know that the length of the wedge is "slow," then the length of the apatite must be "fast," c = X and the sign is negative. The test may be applied to any vertical section of a dimetric mineral if we know the position of the crystallographic axis c in the section.

Optic Orientation of Trimetric Minerals.—It has been seen in the foregoing account of dimetric crystals

i. That in any anisotropic section there are two vibration directions which are perpendicular;

ii. That the two rays penetrating such a section are propagated with different velocities;

iii. That in a section containing the crystallographic axis c, the difference of velocity (indicated by the polarisation colour) is at a maximum;

iv. That in such a section the vibration directions are respectively parallel to and perpendicular to the crystallographic axis *c*;

v. That the vibration directions giving extremes of velocity are known as ether axes;

vi. That the sign of the double refraction may be determined by use of the wedge.

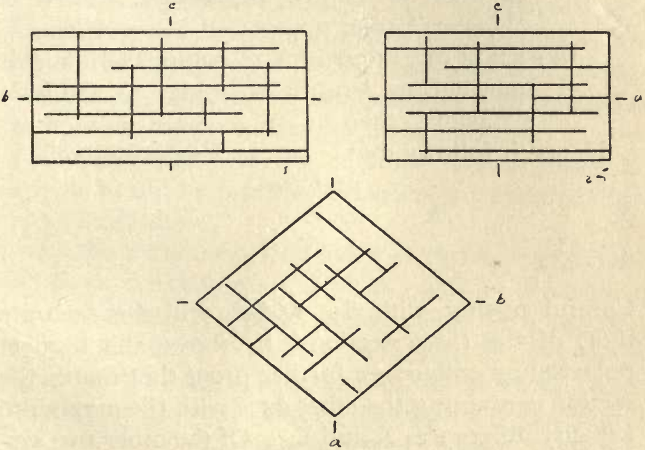
It will be seen that in a dimetric crystal there are many possible sections parallel to *c*, but all these have the same polarisation colours, and hence each contains two ether axes. We have to regard such a crystal as having, one ether axis coinciding with the crystallographic axis *c*, and an infinite number of other ether axes lying in a horizontal plane. In the case of the orthorhombic system, however, such is not the case. It is found that a section containing the *a* and *c* crystallographic axes (the brachypinacoid, 010) polarises in colours different from, and sometimes very much different from, those given by the section containing *b* and *c* (the macropinacoid 100). It is also found that the section perpendicular to *c* (the basal pinacoid, 001), is not isotropic.

Clearly there are some striking differences between the optical properties of a dimetric mineral and those of an orthorhombic mineral; the two ether axes X and Z, however, still coincide with two crystallographic axes, and it is our object to determine with which of the three crystallographic axes these ether axes coincide. The remaining crystallographic axis, although it is merely the vibration direction of a ray which has some intermediate velocity (not necessarily a mean), is regarded as an ether axis, and is represented by the letter Y.

There are six possible cases within the system :—

1.	2.	3.	4.	5.	6.
$a=X$	$a=X$	$a=Y$	$a=Y$	$a=Z$	$a=Z$
$b=Y$	$b=Z$	$b=X$	$b=Z$	$b=X$	$b=Y$
$c=Z$	$c=Y$	$c=Z$	$c=X$	$c=Y$	$c=X$

The particular case represented by any orthorhombic crystal may be determined if we have three sections parallel to the three pinacoids. Barytes supplies us with a suitable case; fragments are fairly easy to prepare; it is important, however, that the sections should be as nearly as possible parallel to the three pinacoids.



Pinacoidal sections of barytes.
24. Macropinacoid. 25. Brachypinacoid.
26. Basal pinacoid.

By determining the positions of extinction in the three sections, it is found that their vibration directions are, in Figures 24 and 25, parallel to the two cleavages (basal and prismatic, the former being the more perfect), and in Figure 26 that they bisect the cleavage angles; it is also found that they coincide with the crystallographic axes.

Each section should be taken in turn, rotated to a position of maximum illumination, and tested with the slow wedge, in two such positions if necessary, to find the position of compensation.

It is found that:—

In section i., in position of compensation, c is parallel to the length of wedge. $\therefore c$ is "faster" than b.

In section ii., in position of compensation, c is parallel to length of wedge. $\therefore c$ is "faster" than a.

In section iii., in position of compensation, b is parallel to length of wedge. $\therefore b$ is "faster" than a.

Hence it follows that

$$c>b>a$$

$$\& \quad a=Z$$

$$b=Y$$

$$c=X$$

Careful testing with the wedge will demonstrate that, of the three sections, ii. shows the highest polarisation colours—a further proof that that is the section containing the ether axes with the maximum velocity difference, X and Z. Of the other two sections, iii. exhibits polarisation colours almost as high as those of ii., very different from those of i.—a demonstration, if such be required, that the velocity of the ray vibrating in Y is not a mean between the two extremes.

The sign of double refraction cannot be obtained with certainty without the use of convergent polarised light.

The three ether axes, X, Y and Z, exist in all three trimetric systems, that is, the orthorhombic, monoclinic, and triclinic. In the last two systems, however, as the crystallographic axes are not, and as the ether axes are always, at right angles, the two kinds of axes cannot coincide. In the monoclinic system, the *b* crystallographic axis is coincident with one of the ether axes (X, Y, or Z), while the remaining two lie in the plane of symmetry. The situation of those two may be ascertained by measuring the extinction in a section parallel to the plane of symmetry (the clinopinacoid, 010). Neither of these ether axes necessarily coincides with either the crystallographic axis *a* or *c*.

The symmetry of the triclinic system being so low, it would be profitless to attempt a statement of optic orientation.

In the foregoing statement of optic orientation, we have considered only those sections containing two ether axes. Other sections have been ignored as introducing unnecessary difficulty at the present stage. It is quite evident that, as a section may take any direction whatever through a crystal, only a few of these will contain two ether axes; some will contain one only, while in the majority of cases the section will not contain any. Nearly all these, however, are doubly refracting, and must therefore contain two vibration directions. A full statement of the case may be postponed for the present, but it may be pointed out that:—

In sections containing two ether axes, vibration takes place parallel to them.

In sections containing one ether axis only, the vibration directions are respectively parallel to and perpendicular to this direction.

CHARACTERS OF MINERALS BETWEEN CROSSED NICOLS IN CONVERGENT LIGHT

In considering the examination of transparent mineral plates, it has already been seen that there are three conditions of the microscope, all of which must be used in turn if we are to acquire a satisfactory amount of information in regard to the minerals in thin section. Even after this examination, it is not always possible to say with certainty that a particular mineral has been satisfactorily identified. The need for some further information is sometimes keenly felt. Convergent polarised light often supplies us with a means of acquiring the required information.

Methods of Obtaining an Interference Figure.— In fitting up the microscope, the instrument is first arranged as for use with parallel polarised light. The high power objective (usually ¼in.) must be used. A system of converging lenses is fitted either beneath the stage or above the polariser, and a lens (the Bertrand lens) is placed in the tube of the microscope, either sliding in by means of a slot or fixed to the lower end of a draw tube. It is necessary to point out that some of these adjustments must be made with care, as the best results are not always obtained. Students should be quite sure that the nicols are in use and crossed, that the mirror is adjusted to give the best possible illumination, that the Bertrand lens is in position, and that the converging lenses occupy their place between polariser and stage.

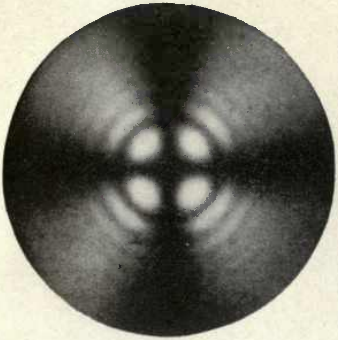
The effect may often be further improved by adjusting the objective and the converging system to the best advantage. The interference figure obtained in these circumstances with suitable sections of doubly refracting minerals is the best obtainable; but although the Bertrand lens is a necessity if determinations of sign are to be made, it is not absolutely necessary in order to obtain a view of the figure.

If all the adjustments here described, with the exception of the insertion of the Bertrand lens, have been effected, the figure may be focussed by means of an ordinary pocket lens held a little way (usually between 1in. and 3in.) above the eyepiece. The figure may also be observed without the Bertrand lens if the eyepiece also is removed.

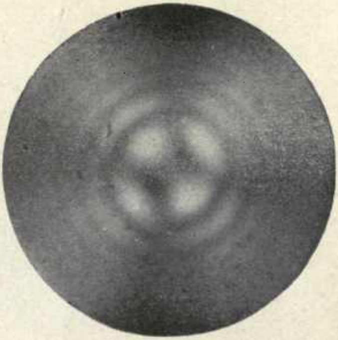
It is sometimes useful to know the last two methods, because, although the figure obtained is not so large as that obtained with the Bertrand lens, it is perhaps rather more clear. In the following description, however, it will be assumed that the lens is in use.

Uniaxial and Biaxial Interference Figures.—The interference figure is seen when a suitable section of a doubly refracting mineral is examined in convergent light, and is one of two types. One of these is obtained when a basal section of a dimetric mineral is examined; the other when the section is

PLATE I

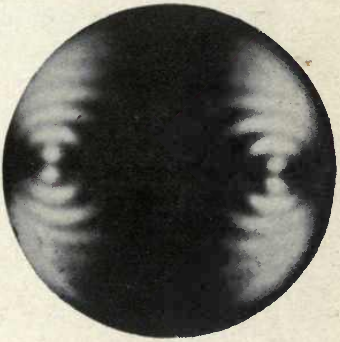


1.—Uniaxial interference figure.

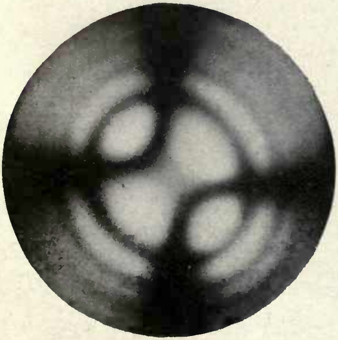


2.—Uniaxial interference figure
Mica plate introduced.

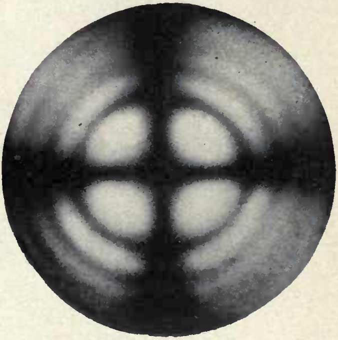
3.—Biaxial interference figure. Oblique position.



4.—Biaxial interference figure.
Straight position.



5.—Pseudo-uniaxial interference figure.
Oblique position.

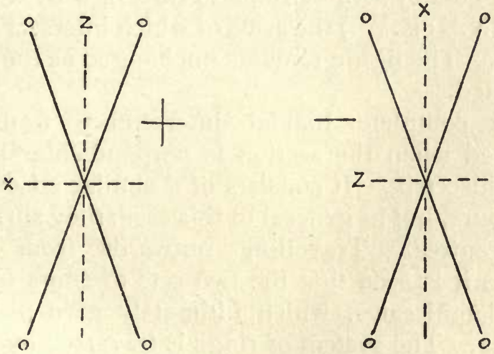


6.—Pseudo-uniaxial interference figure.
Straight position.

To face page 51.

cut from a trimetric mineral perpendicular to the X or Z ether axis.

It has been seen that, in general, when light is transmitted through a section of a doubly refracting mineral, it is split up into two rays having different velocities. There are sections of such minerals, however, perpendicular to which light is transmitted with one velocity only. These directions of propagation are known as optic axes. Dimetric crystals have one such direction, which coincides with the *c* crystallographic axis; they are hence referred to as *uniaxial*. Trimetric crystals have two such directions, and are consequently referred to as *biaxial*. It is always the case that these two optic axes lie in a plane which contains also the X and Z ether axes, and that they are situated symmetrically with regard to them; that is, X and Z bisect the angles between the optic axes.



Optic axes and ether axes in biaxial crystals.
27. Positive. **28. Negative.**

There are two cases:—

- i. Z bisects the acute angle: double refraction positive.
- ii. X bisects the acute angle: double refraction negative.

In either case Y is perpendicular to the plane containing the optic axes (the optic axial plane) and is known as the optic normal.

The complete uniaxial interference figure is obtained when the section is perpendicular to the optic axis. It consists, as a rule, of a series of concentric circles which give Newton's scale of colours; the succession of colours when traced from the centre outwards is the same as that previously obtained with the wedge, commencing with the thin end. This system of rings is traversed by a black cross (N.S : E.W.) the arms of which intersect at the centre. The figure remains unchanged as the stage is rotated.

The complete biaxial interference figure is obtained when the section is perpendicular to the acute bisectrix. It consists of a similar succession of colours, but in general in this case, they surround two centres. Travelling outwards from these centres it is seen that the two sets of rings fuse to form lemniscates, which ultimately give place to ellipses. The system of rings is traversed by black bands, but in this case there is a striking change as the stage is rotated. There is always a black band traversing each "eye"; the bands form a cross when the trace of the optic axial plane (the line joining the two eyes) is situated N.S. or E.W. When that line is situated N.E : S.W. or N.W : S.E., the cross has split into hyperbolæ, one traversing each eye.

It is instructive to study the effects of variation in thickness in the case of minerals showing the two types of figure. This can be done conveniently in the case of minerals which have a good cleavage in the direction of section, such as the two micas, biotite and muscovite. Biotite is not an ideal case, but it is convenient; it shows a figure which is only approximately uniaxial, though the approximation is usually sufficiently close. A cleavage flake which is fairly thick should be selected and placed (unmounted) on the stage. If the section is thin enough to transmit the light, a uniaxial interference figure with several rings will be seen. Successive observations should be made on thinner and thinner flakes, and it will be seen that the number of rings in the field decreases until the final stage is reached with the innermost ring outside the field. The black cross, however, persists.

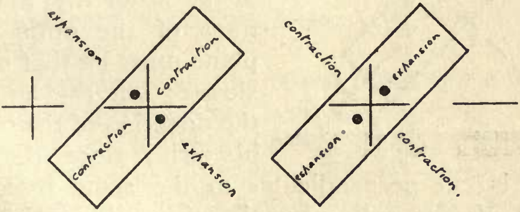
Muscovite supplies us with an almost perfect example of a biaxial interference figure. The process of examining progressively thinner flakes should be repeated, preferably with the figure in an oblique position. It is found that the rings expand around the eyes until even the innermost ring has given place to a lemniscate or an ellipse, or has even disappeared beyond the limits of the field. Here again the hyperbolæ persist throughout in the same position.

A similar change is observed if a series of minerals is examined in section (the sections should be of a constant thickness) commencing with one having a high double refraction and proceeding to those with lower and lower double refraction. A similar expansion is observed analogous in the case of uniaxial minerals, to the thinning of biotite, and in the case of biaxial minerals to the thinning of muscovite.

An examination of a biaxial series also demonstrates the fact that in some cases the eyes come nearer together than in others; the distance between them being roughly a measure of the optic axial angle (the acute angle). This variation in the value of the optic axial angle would seem to suggest that there is no reason to suppose that there is any sharp distinction between uniaxial and biaxial minerals; the former may be regarded as a special case of the latter, where the optic axial angle has become so small as to be difficult to measure. Biotite is an example of a mineral which is certainly biaxial, because, as the stage is rotated, the black cross is seen to split up into hyperbolæ; but the optic axial angle is so small that the figure never shows two eyes even in thick sections.

Sign of Uniaxial Minerals.—It is not necessary that a mineral section which has been prepared specially to give an interference figure should have the same thickness as an ordinary rock section, in fact, it is only in the case of minerals with a very high double refraction that such a thin section gives the best results. As a rule, minerals in thin section, when examined in convergent polarised light, exhibit no coloured rings, but only a black cross or hyperbolæ. Students must be prepared, then, to find that the figures to be examined will be very variable as to the number of coloured rings in the field. Even supposing the thickness to be constant, the number of rings in the field will, as has been seen, be dependent on the birefringence.

Fortunately, however, there is one method which can be used in order to determine the sign of any uniaxial mineral showing a complete figure. That method involves the use of a mica plate. This is a small rectangular flake of muscovite, cut in such a way that its slow vibration direction is parallel to the length of the rectangle. It should be mounted on a glass slip ½in. in width. Having obtained the figure, the mica plate should be inserted into the slot immediately above the objective. It has the effect of producing expansion in one pair of opposite quadrants, and contraction in the other pair. Where expansion takes place, two black spots appear near the centre of the field. There are two cases.

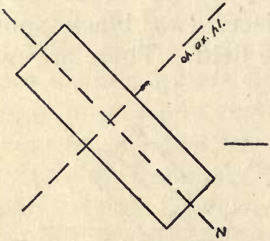


Sign of uniaxial minerals with mica plate.
29. Positive. 30. Negative.

When the double refraction is positive, a straight line joining the two spots would lie perpendicular to the length of the plate, and when negative, parallel to the length.

The same method may be used in order to determine the sign of a biaxial mineral (such as biotite) with small optic axial angle.

Sign of Biaxial Minerals.—Having obtained the figure, the stage should be turned so that the trace of the optic axial plane occupies an oblique position (say N.E : S.W.). The converging apparatus should be removed and the section examined in parallel polarised light by means of the low power objective. Testing with the wedge, the stage remaining in the same position, will give either compensation, or will raise the polarisation colours.



31. Compensation with a slow wedge for a negative biaxial crystal.

If compensation is obtained with the optic axial plane N.E : S.W. using a slow wedge, then, as the length of the wedge is parallel to the optic normal, that direction must be the vibration direction of the faster ray, and the trace of the optic axial plane must be that of the slower; but the latter is the direction of the obtuse bisectrix, since the section is cut perpendicular to the acute bisectrix. Then Y (the optic normal)>obtuse bisectrix, that is, the obtuse bisectrix=Z. The acute bisectrix must therefore be X, and the double refraction is negative.

When the double refraction is positive, compensation is obtained when the slow wedge is inserted parallel to the trace of the optic axial plane.

It is possible to determine the sign of a mineral showing a biaxial figure without removing the converging apparatus. The wedge or mica plate should be inserted into the lower slot while the figure (with the optic axial plane N.W : S.E. or N.E : S.W.) is carefully observed. There will be one of two effects. Either the rings will become lemniscates or the lemniscates will become rings. In the first case opposition is taking place; in the second case, coincidence. The sign may be determined by a process of reasoning similar to that described for the preceding method.

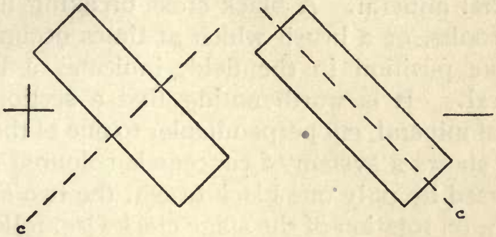
Partial Interference Figures. — A complete uniaxial interference figure is given only by a section which is perpendicular to the vertical axis of a dimetric crystal (the optic axis); but as only a small minority of the fragments in a rock section are cut in that direction, it is desirable to have some method of determining the sign of double refraction of a mineral when the section has some other orientation.

The appearance of the partial interference figure depends largely on the obliquity of the section examined. In the case of a section which is almost perpendicular to the optic axis, the centre of the figure may be in the field of the microscope, but will not coincide with the centre of the field; rotation of the stage causes the centre of the figure to describe a circle concentric with that limiting the field. In such a case the sign may be obtained by using a mica plate as with a complete figure.

A section departing still further from the position of that giving a complete figure may show only a portion of the system of rings on the margin of the field, or these may be entirely outside its limits, but in any case the arms of the black cross will sweep across the field as rotation takes place. The movement of these arms must be observed if the sign is to be determined.

Let it be supposed that the centre of the figure is somewhere outside the field away towards the N.E. On rotation of the stage in the clockwise direction, a horizontal arm sweeps across the field from N. to S., then a vertical arm from E. to W., then a horizontal arm from S. to N., and immediately before a complete rotation has taken place, a vertical arm from W. to E. The succession of events may be illustrated by holding two penholders at right angles to form a cross, resting a coin on the table, and, with the centre of the cross, describing a circle of greater diameter than that of the coin but concentric with it, so that the arms of the cross, while retaining their N.S. and E.W. directions, sweep in turn over the coin. It will be seen, then, that it is possible to locate the centre of the figure after a rotation of the stage has been completed.

The centre of the figure should be placed so that a straight line joining it with the centre of the field bisects one of the angles formed by the cross-wires, say to the N.E. Having got that in position, remove the converging apparatus and examine in parallel polarised light between crossed nicols with the low power objective. Test with the slow wedge, on the assumption that the straight line joining the two centres (field and figure) is the vertical axis *c*.



Compensation with a slow wedge and uniaxial crystals.
32. Positive. 33. Negative.

The wedge being inserted in a N.W : S.E. direction, compensation in that position indicates positive double refraction, because $c = Z$. If compensation is obtained with the centre of the figure in the N.W : S.E. line, the double refraction is negative, because $c = X$.

The sign of a mineral in section showing only a partial biaxial figure can only be obtained by means of more complex methods.

In applying the test of convergent polarised light to a doubly refracting mineral in thin section, the information desired is:—

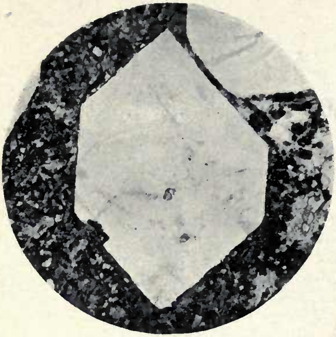
i. Is the mineral uniaxial or biaxial?
ii. What is the sign of its double refraction?

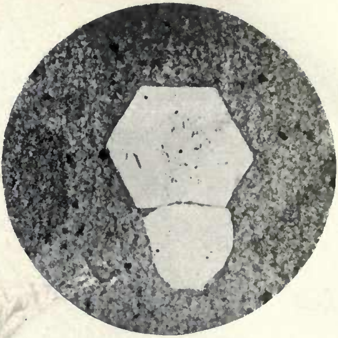
One of the difficulties encountered is that the section is probably too thin to show anything of the coloured rings, but the " brushes " ought always to be visible in a well-selected crystal. As a rule the fragment chosen should be the one giving the lowest polarisation colours. A black cross which remains unbroken on rotation, or vertical and horizontal brushes sweeping across the field, indicate a uniaxial mineral. A black cross breaking up into hyperbolæ, or a brush which at times occupies an oblique position in the field, indicates a biaxial mineral. It is worth noting that a section of a biaxial mineral, cut perpendicular to one of the optic axes, shows a system of concentric coloured circles traversed by only one black brush, the two ends of which, on rotation of the stage clockwise, follow the margins of the field in the anti-clockwise direction. The movements of that brush are of considerable importance in the examination of thin sections.

After the determination of the kind of figure, the sign of the double refraction should be obtained. This may be done in all cases where a complete figure is exhibited, and in the case of a uniaxial mineral, even where only a partial figure is seen.

DESCRIPTIONS OF COMMON ROCK-FORMING MINERALS.

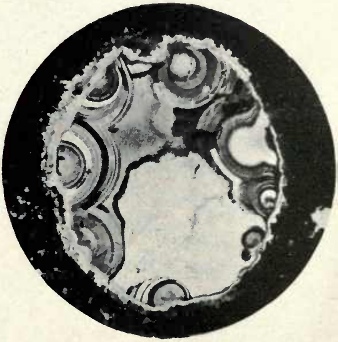
PLATE II


1.—Quartz. Ordinary Light. Vertical section. Showing form.


2.—Quartz. Ordinary Light. Basal section. Showing form.


3.—Quartz. Ordinary Light. Showing corrosion.


4.—Quartz. Ordinary Light. Showing


5.—Chalcedony in amygdule. Ordinary Light.

DESCRIPTIONS OF ROCK-FORMING MINERALS

FORMS OF SILICA

Quartz.—SiO_2. *Hexagonal. Birefringence positive.*

Colour.	None.
Form.	Commonly allotriomorphic, but occasionally showing hexagonal outlines.
Cleavage.	None.
Ref. Index.	1·55. A little higher than that of Canada balsam.
Alteration.	None.
Inclusions.	Minute liquid and gas inclusions sometimes seen with ¼″ objective.
Pol. Colours.	1st order. Basal sections isotropic.
Twinning.	None.

It will be seen that the majority of the characters are negative; there is never any colour, cleavage, alteration, or twinning; rarely any form, and the refractive index is not such as to give any high relief. The absence of definite characters is the fact to be borne in mind by the student.

Tridymite	SiO_2. A rare and unimportant variety of silica usually occurring as nests of scale-like crystals.
Chalcedony	SiO_2. A secondary form of silica found filling cavities. Usually in pale shades of brown, showing concentric arrangement. Between crossed nicols, shows a very characteristic aggregate polarisation, with black crosses due to radiating crystals.
Opal	SiO_2nH_2O. Also occurs filling interstices, and much like chalcedony in ordinary light, but distinguished by its isotropism between crossed nicols.

FELSPARS

Orthoclase.
Plagioclase.
  Microcline.
  Albite-Anorthite Series.

The common felspars are silicates of aluminium with potassium, sodium, or calcium. Orthoclase felspar crystallises in the monoclinic system; the plagioclase felspars crystallise in the triclinic system. All possess cleavages parallel to 001 (basal pinacoid), and 010 (clinopinacoid or brachypinacoid).

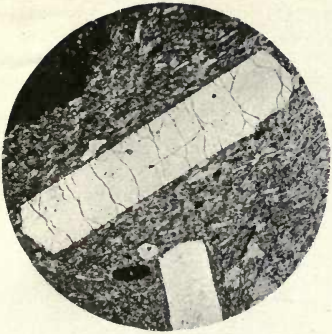
Orthoclase.—$KAlSi_3O_8$. *Monoclinic.*

Twinning.	*Manebach.*	*Twin*	*plane*	001 (*basal pinacoid*).
	Baveno.	,,	,,	021 (*clinodome*).
	Carlsbad.	,,	,,	100 (*orthopinacoid*).
	,,	*Comp.*	,,	010 (*clinopinacoid*).

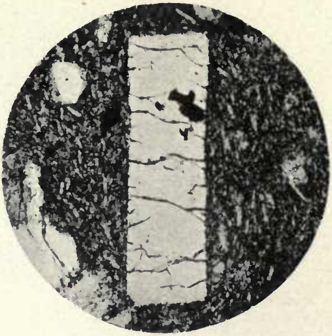
Birefringence negative.

Colour.	None.
Form.	Sometimes idiomorphic, when rectangular or hexagonal sections are shown. Often allotriomorphic.
Cleavage.	In favourable sections two rectangular cleavages are seen, but some sections show one cleavage only; other sections show no cleavage.
Ref. Index.	1·52. Slightly less than, but very near to, that of Canada balsam.
Alteration.	Often turbid in consequence of alteration, but may be quite or partially transparent.
Pol. Colours.	1st order; greys, white, and yellow.
Extinction.	Commonly oblique, but sometimes straight.
Twinning.	Absent or simple.

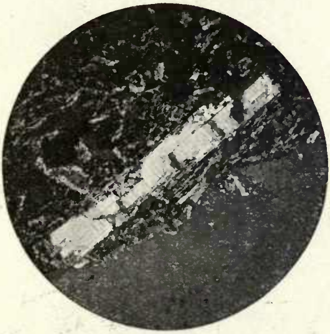
PLATE III



1. Orthoclase. Ordinary Light. Showing form.



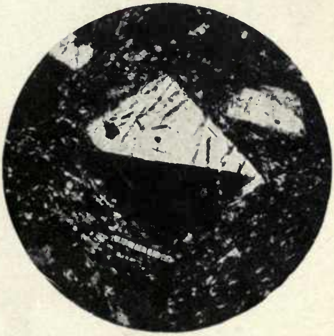
2.—Orthoclase. Ordinary Light. Showing form.



3.—Orthoclase. Crossed nicols. Showing cleavages.

4.—Orthoclase. Ord. L. Showing alteration and intergrowth with quartz.

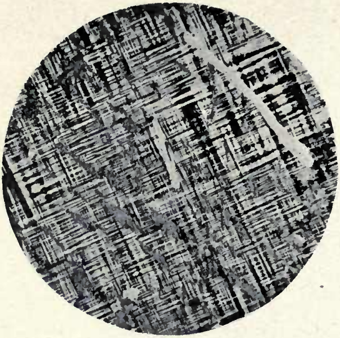
5.—Orthoclase. Crossed nicols. Showing Carlsbad twinning



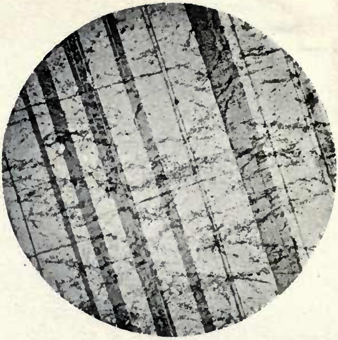
6.—Orthoclase. Crossed nicols. Showing Baveno twinning.

To face page 68.

PLATE IV



1.—Microcline. Crossed nicols. Showing cross-hatching.



2.—Plagioclase, ab.-an. ser. Crossed nicols. Showing lamellar twinning.

3.—Plagioclase, ab.-an. ser. Ordinary Light. Showing zoning by alteration.

4.—Plagioclase, ab.-an. ser. Crossed nicols. Showing lamellar twinning.

5.—Plagioclase, ab.-an. ser. Ord. L. Showing zoning by inclusions.

6.—The same. Crossed nicols. Showing zoning and lamellar twinning.

To face page 69.

Microcline.—$KAlSi_3O_8$. *Triclinic. Birefringence negative.*

This mineral cannot be distinguished in ordinary light from orthoclase, but between crossed nicols it shows lamellar twinning in two directions, the two sets often intersecting at angles approaching 90°. The pattern produced is that known as cross-hatching.

Albite-Anorthite Series.—*Triclinic. Twin plane* 010 (*brachypinacoid*).

The minerals in this series form an isomorphous group, with albite and anorthite at the two extremes. The members of the series cannot be said to have any well-defined individuality, as the several mineral names do not imply any definite composition.

The composition range of the several members of the series is illustrated below, where the albite molecule (Ab) $NaAlSi_3O_8$, and the anorthite molecule (An) $CaAl_2Si_2O_8$, are combined in the various proportions.

	Ab.	An.	Ref. Index.
Albite	10	0	1·53
	9	1	
Oligoclase	8	2	1·54
	7	3	
Andesine	6	4	1·55
	5	5	
Labradorite	4	6	1·56
	3	7	
Bytownite	2	8	1·57
Anorthite	1	9	
	0	10	1·58

An inspection of the above table will show that labradorite, for example, may have as little as 25% Ab. or as much as 50% Ab.

The members of this Ab. An. series are distinguished from orthoclase by the lamellar twinning seen when examined between crossed nicols. It is desirable also to distinguish between the different members of the series, but the distinction is a matter of some difficulty. The most commonly accepted method is based on the extinction angle, as measured from the twin striations, the extinction angle being greatest at the Anorthite end of the series. The beginner, however, is recommended to remain satisfied with having recognised the mineral as plagioclase felspar (Ab. An. series). He can later make himself familiar with the method of extinction or make use of the variation in refractive index. It will be seen that the refractive index of oligoclase is equal to that of Canada balsam. If the refractive index is less than 1·54 the felspar may be called albite; if greater than 1·54, the degree of relief may be used as a means of getting the approximate place of the felspar in the series.

Resemblances.—The distinction between orthoclase, microcline, and the Ab. An. series, is easily effected by a consideration of the kind of twinning. Quartz, however, is not always easy to distinguish from orthoclase. In difficult cases a careful search should be made for cleavage, alteration, and twinning. The presence of any one of these would eliminate quartz. The distinction may also be effected in convergent light; quartz is uniaxial, and orthoclase biaxial.

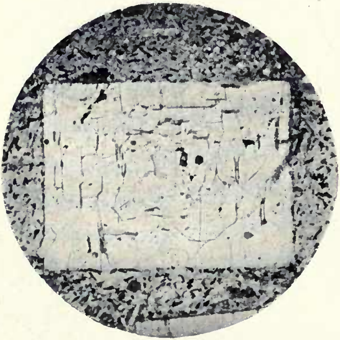
PLATE V

1.—Leucite. Ordinary Light. Showing form.

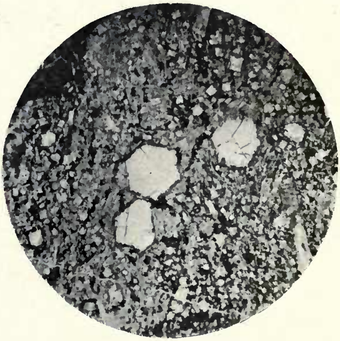
2.—The same. Crossed nicols. Showing cross-hatching.

3.—Leucite. Ordinary Light. Showing inclusions.

4.—Nosean. Ordinary Light. Showing zoning.



5.—Nepheline. Ordinary Light. Showing form of vertical section.



6.—Nepheline. Ordinary Light. Showing form of basal sections.

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FELSPATHOIDS

Leucite.—$KAl(SiO_3)_2$. *Cubic* (?).

Colour.	None when fresh.
Form.	Sometimes octagonal, but usually rounded.
Cleavage.	None.
Ref. Index.	1·51. Sufficiently different from that of Canada balsam to have a fairly good relief.
Alteration.	May be quite fresh, but occasionally turbid and pale brown through alteration.
Inclusions.	Sometimes contains included fragments arranged radially or concentrically.
Pol. Colours.	May be quite isotropic, but often polarises in dark greys and shows intersecting twin lamellæ resembling those of microcline.

Resemblances.—May be confused with microcline, but it has a better relief in ordinary light, and a lower double refraction.

Nosean.—*Silicate and sulphate of sodium and aluminium. Cubic. Cleavage* 110 (*Rhomb-dodecahedral*).

Colour.	None or brown.
Form.	Very variable. Often irregular, but sometimes showing hexagonal outlines.
Cleavage.	Occasionally, but not often, seen.
Ref. Index.	1·46. Has a good relief in consequence of its very low refractive index, but the common thick dark border is due to inclusions—not to refractive index.
Alteration.	To aggregates of zeolites—producing turbidity.
Inclusions.	Sometimes packed with dark brown inclusions, but often these are localised at the margins, giving a striking zoned appearance.
Pol. Colours.	Isotropic when fresh, but showing aggregate polarisation when decomposed.

Hauyne.—*Composition similar to that of nosean but with calcium silicate and sulphate in addition. Cubic.*

Often very similar to Nosean in appearance, but more commonly has inclusions localised at the centre, and sometimes shows blue or green colour.

Nepheline.—*Composition* $\left\{\begin{matrix} \mathrm{m\ NaAlSiO_4.} \\ \mathrm{n\ \ KAl(SiO_3)_2.} \end{matrix}\right\}$ *Hexagonal. Cleavages prismatic and basal. Birefringence negative.*

Colour.	None when fresh, but brownish when altered.
Form.	Rectangular or hexagonal.
Cleavage.	Rarely seen.
Ref. Index.	1·54. Very nearly equal to that of Canada balsam.
Alteration.	May be fresh, but often found decomposed to radiating aggregates of small acicular crystals.
Pol. Colours.	Basal sections isotropic; other sections polarising in greys (1st order).
Extinction.	Straight.
Twinning.	None.

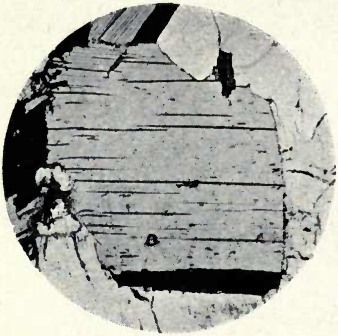
Resemblances.—May be distinguished from felspars by its more common rectangular and hexagonal sections, its different type of alteration, its lower polarisation colours and isotropic sections, its straight extinction and the absence of twinning; also by examination in convergent light.

The variety found in coarse-grained igneous rocks is known as Elæolite.

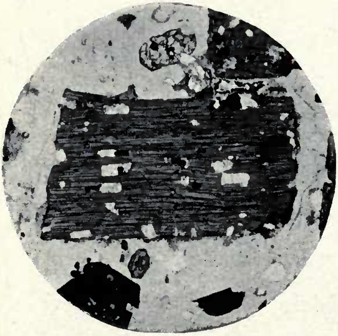
Sodalite.—*Silicate and chloride of sodium and aluminium. Cubic. Cleavage* 110 (*Rhomb-dodecahedral*).

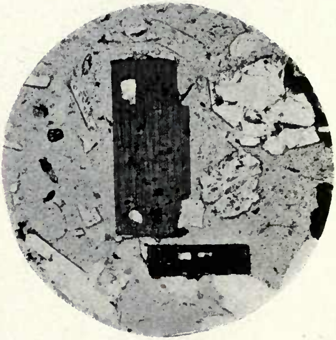
Colour.	None.
Form.	Allotriomorphic.
Cleavage.	Not always seen, but may be found in several directions.
Ref. Index.	1·48. Approximating to, but less than, that of Canada balsam.
Alteration.	Occasionally turbid through decomposition, but usually clear.
Polarisation.	Isotropic.

PLATE VI

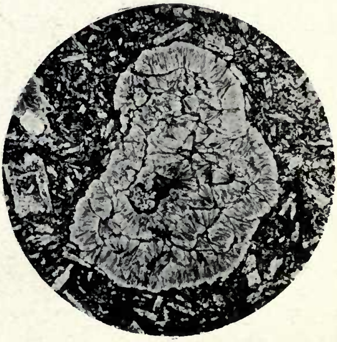

1.—Muscovite. Ord. L. Showing cleavage.


2.—Muscovite. Ord. L. Showing cleavage and intergrowth with biotite.


3.—Biotite. Ord. L. Showing form, cleavage and inclusions.


4.—Biotite. Pol. L. Showing pleochroism.


5.—Biotite. Ord. L. Showing partial alteration to chlorite.


6.—Chlorite. Ord. L. Showing vermicular habit and occurrence in amygdule.

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MICAS

Characterised by their perfect basal cleavage and pseudo-hexagonal symmetry. Muscovite and Biotite are selected as examples of the group.

Muscovite.—*Comp.* $H_2KAl_3(SiO_4)_3$. *Monoclinic. Cleavage* 001. (*Basal*). *Birefringence negative.*

Colour.	None.
Form.	Allotriomorphic.
Cleavage.	One direction of cleavage nearly always seen.
Ref. Index.	1·58. No very striking relief, but still evidently much different from Canada balsam.
Alteration.	None.
Pleochroism.	Since the mineral is colourless in thin section, there cannot be any pleochroism; but occasionally it is found that around minute inclusions the mineral is a pale brown, and these haloes are pleochroic.
Pol. Colours.	Bright pinks and greens.
Extinction.	Straight.
Twinning.	None.

Resemblances.—Muscovite cannot be mistaken for any of the minerals previously described. Even ignoring other tests, the polarisation colours are sufficiently distinctive.

Biotite. — *Comp.* $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$. *Monoclinic. Cleavage* 001 (*Basal*). *Birefringence negative.*

It has many characters in common with Muscovite, but differs in the following respects:—

Colour.	Brown.
Alteration.	Decomposes to a green product, Chlorite, which is sometimes pseudomorphous; but all stages in the alteration are to be seen.
Pleochroism.	Strong : from pale brown to dark brown.
Pol. Colours.	Commonly obscured by the absorption colour.

Resemblances.—The brown colour and pleochroism are sufficient to distinguish the mineral from any one of the preceding minerals.

OTHER MICACEOUS MINERALS

Chlorites.—*Basic silicates of iron, aluminium, and magnesium. Monoclinic. Cleavage* 001 (*Basal*).

Colour.	Green.
Form.	Usually as pseudomorphs after unstable ferromagnesian silicates which contained alumina; *e.g.*, biotite. Sometimes in parallel or radiating aggregates; sometimes vermicular.
Cleavage.	In one direction only.
Ref. Index.	About 1·58.
Pleochroism.	Slight: pale green to darker green.
Pol. Colours.	1st order greys: often masked by absorption. Sometimes shows ultra-blues or ultra-browns.
Extinction.	Straight.

Chloritoids.—*Composition approximating to that of Chlorite. Monoclinic or Triclinic.*

Colour.	Indigo blue or greenish black.
Form.	Variable, but sometimes rectangular.
Cleavage.	One direction good: others obscure.
Ref. Index.	Variable, but always high.
Inclusions.	Abundant.
Pleochroism.	Usually from indigo blue to greenish yellow.
Pol. Colours.	1st order greys.
Extinction.	Usually oblique.
Twinning.	Common.

Resemblances.—Differ from Chlorites in having a high refractive index, often a curious indigo blue colour, and many inclusions. Pleochroism also is distinctive, usually from indigo blue to greenish yellow.

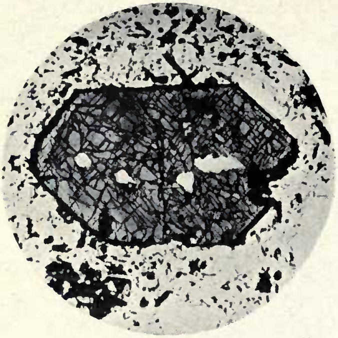
Talc.—$H_2Mg_3(SiO_3)_4$. *Monoclinic* (?).

Very much like Muscovite, but has a slightly lower refractive index, 1·56, and a little higher birefringence.

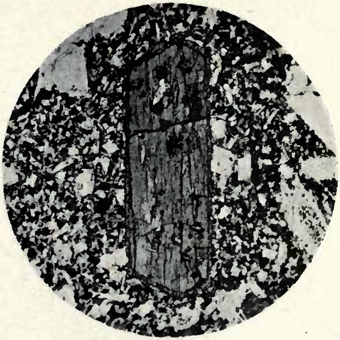
PYROXENES

The pyroxenes fall into a fairly well-defined group of minerals with a tendency to form crystals

PLATE VII



1.—Aegerine, transverse section. Ordinary Light. Showing form and cleavages.

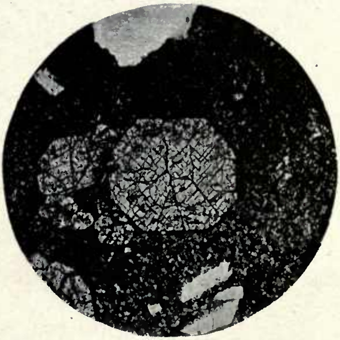


2.—Augite, vertical section. Ordinary Light. Showing form.

3.—Augite, vertical section. Ordinary Light. Showing form and zoning.

4.—Augite, trans. sect. Crossed nicols. Showing form, zoning and simple twinning

5.—Augite. Crossed nicols. Showing zoning and "hour-glass" structure.



6.—Enstatite, transverse section. Ordinary Light. Showing form and cleavages.

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with eight vertical faces, four of these being prism faces meeting at angles which are approximately 90°. All of them have prismatic cleavages which intersect at the prism angle. Composition, variable.

Monoclinic Pyroxenes

Augite.—*Silicate of calcium, iron, magnesium and aluminium. Monoclinic. Cleavage* 110 (*Prismatic*). *Twin plane* 100 (*Orthopinacoid*). *Birefringence positive.*

Colour.	Brown.
Form.	Transverse sections sometimes octagonal.
Cleavage.	In transverse sections, two at right angles. Other sections may show one only, or even none.
Ref. Index.	1·72. The mineral has a good relief and the cleavages and other cracks are conspicuous.
Alteration.	Sometimes to green chlorite, occasionally to hornblende.
Pleochroism.	Typically none: but some varieties show feeble pleochroism.
Pol. Colours.	Bright colours, commonly 2nd and 3rd order.
Extinction.	Commonly oblique, but sometimes straight.
Twinning.	Simple and lamellar.

Diopside.—*Silicate of calcium, iron and magnesium.*

Differs from Augite only as regards colour—it is green instead of brown.

Aegerine.—*Silicate of sodium and iron.*

Sections of this pyroxene are also green, but, as the mineral is strongly pleochroic, the different fragments seen in ordinary light exhibit different shades of green, ranging from blue green to yellow green—two extremes which are seen when the mineral is examined with the aid of the polariser.

Diallage.—*Similar to augite in composition.*

Distinguished by the possession of an extra cleavage (pinacoidal) and by a fibrous, woody appearance when seen in ordinary transmitted light.

Orthorhombic Pyroxenes

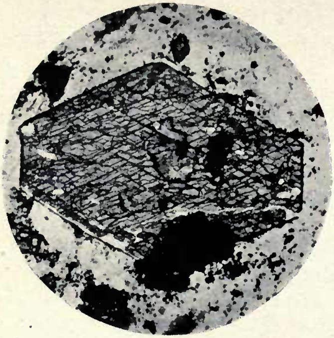
These form an isomorphous series, with Enstatite, $MgSiO_3$, birefringence positive, and Hypersthene $(Mg,Fe)SiO_3$, birefringence negative, at the two extremes. It is usual to recognise an intermediate member of the series in Bronzite.

They differ from Augite in having a lower refractive index (enstatite 1·67 and hypersthene 1·70), and also in their polarisation. 1st order colours are common, but hypersthene occasionally shows 2nd order colours. There is a tendency for the octagonal outline of transverse sections to become regular. Hypersthene also shows a peculiar pleochroism — blue-green to reddish brown. Straight extinction is much more common than oblique extinction, the reverse of what is the case with the monoclinic pyroxenes.

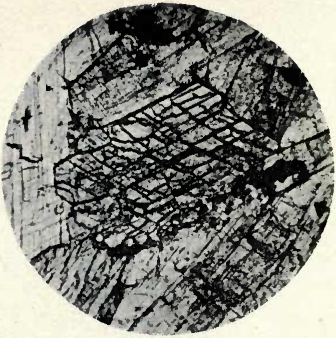
AMPHIBOLES

As in the case of the pyroxenes, the amphiboles form an isomorphous series. In crystals of this group, however, only six vertical faces are usually found; the four prism faces meeting at angles of about 125° and 55°. The prismatic cleavages, of course, intersect at these angles. The amphiboles resemble the pyroxenes in many respects, not the least important being that of composition; and, in general, for any pyroxene, an amphibole can be found having the same empirical formula.

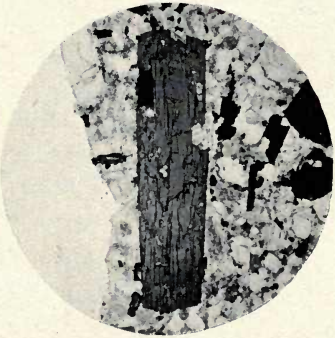
PLATE VIII



1.—Hornblende, transverse section. Ord. L.
Showing form and cleavages.

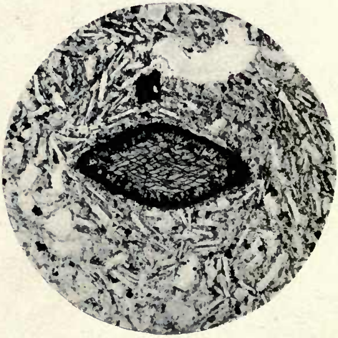


2.—Actinolite, transverse section. Ord. L.
Showing form and cleavages.



3.—Hornblende, vertical section. Ord. L.
Showing form and cleavage.

4.—Glaucophane, trans. sect. Ord. L.
Showing form and cleavages.



5.—Hornblende, trans. sect. Ord. L.
Showing alteration rim.

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As there are many points of resemblance between the two groups, it is desirable to point out the characters by which we are enabled to distinguish between them; the most important are:—(1) the form, and (2) the cleavage angle.

Hornblende.—*Silicate of calcium, iron, magnesium, and aluminium. Monoclinic. Cleavage* 110 (*prismatic*). *Twin plane* 100 (*orthopinacoid*). *Birefringence negative.*

Colour.	Green or brown.
Form.	Transverse sections often show six-sided outline.
Cleavage.	Transverse sections show two intersecting at 125°.
Ref. Index.	1·65. Fairly good relief.
Alteration.	Not common, but occasionally pseudomorphed in magnetite or chlorite.
Pleochroism.	Strong: light to dark green, or light to dark brown.
Pol. Colours.	2nd order, but commonly masked by absorption colour.
Extinction.	Commonly slightly oblique; occasionally straight.
Twinning.	Occasional simple twinning.

Actinolite.—*Silicate of calcium, iron and magnesium. Monoclinic.*

Distinguished from green hornblende by its paler green colour.

Tremolite.—*Silicate of calcium and magnesium. Monoclinic.*

Characterised by its entire freedom from colour.

Glaucophane.—*Silicate of sodium, aluminium, and magnesium. Monoclinic.*

Distinguished by its beautiful reddish or bluish-violet colour. In addition to either of these colours a pale greenish yellow is sometimes seen when the test for pleochroism is applied.

Anthophyllite.—$(Mg,Fe)SiO_3$. *Orthorhombic.*

A rather rare mineral which is distinguished from Hornblende by the fact that nearly all sections show straight extinction.

Resemblances of Amphiboles.—It is not always easy to distinguish between pyroxene and amphibole; but in cases of difficulty a careful search should be made for a characteristic outline or cleavage angle.

The only other preceding minerals at all likely to be confused with amphiboles are the Micas. Sections of biotite sometimes resemble hornblende fairly closely; and the difficulty is not minimised by the fact that the two minerals are often found in the same slide. The following will be found useful in making the distinction between the two minerals.

Colour.—This test may be applied with advantage even though both minerals are pleochroic; the different fragments of the two minerals are not similarly coloured.

Form.—Transverse sections of hornblende are easily recognisable when well-formed; it is the elongated longitudinal sections which cause trouble.

Cleavage.—Transverse sections of hornblende again are easily distinguished from biotite by the possession of two cleavages meeting at 125°.

Ref. Index.—This test is useful, as biotite has the lower refractive index.

Pleochroism.—A useful test is found in the fact that biotite when showing the dark extreme of pleochroism, often exhibits a slightly mottled surface never seen in the case of hornblende.

Extinction.—Biotite always shows straight extinction; hornblende sometimes shows oblique extinction. Biotite, again, shows the mottled surface when in extinction.

Tremolite is sometimes difficult to distinguish from muscovite, but careful search should be made for the two cleavages and for oblique extinction, either of which will rule out muscovite.

OLIVINES

Olivine. — $(Mg,Fe)_2SiO_4$. *Orthorhombic. Birefringence positive.*

Colour.	None when fresh, but often associated with green serpentine.
Form.	When idiomorphic, shows hexagons which are irregular, but symmetrical about two of the diameters.
Cleavage.	Rarely seen, but irregular cracks frequent.
Ref. Index.	1.68. Good relief.
Alteration.	Commonly altered to green serpentine and black iron oxide. Alteration commences along the cracks and margins; these gradually grow wider at the expense of the olivine until the final stage, a pseudomorph in serpentine, is reached.
Pol. Colours.	2nd and 3rd orders. Bright colours.
Twinning.	None.

Resemblances.—There is sometimes a difficulty in distinguishing between olivine and augite. Olivine may be distinguished by absence of colour, form (if idiomorphic), absence of cleavage, characteristic alteration.

Olivine is the intermediate member of an isomorphous group of minerals including:—

Forsterite—rich in magnesium. Mg_2SiO_4.
Olivine—
Fayalite—rich in iron. Fe_2SiO_4.

Forsterite is much like olivine, but decomposes to form a colourless serpentine.

Fayalite has a pale greenish colour and a slight pleochroism.

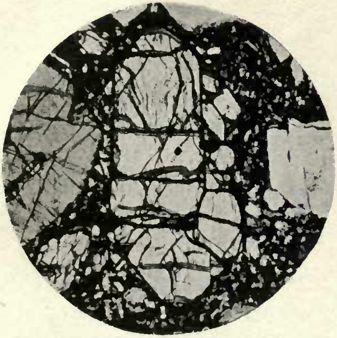
Serpentine.—*Hydrated silicate of magnesium and iron.*

It is easily recognised when associated with olivine or when a pseudomorph after well-formed crystals, but when it occurs as the bulk of large rock-masses, the sections present some difficulty to the beginner.

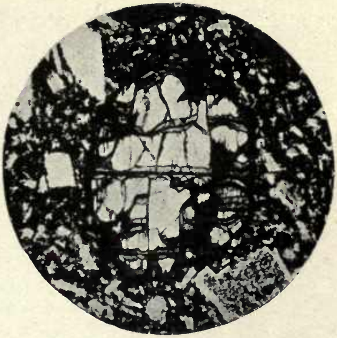
Colour.	Usually pale green or yellow in colour, or may be almost colourless.
Pleochroism.	Occasionally distinct, but usually very feeble.
Pol. Colours.	1st order, greys.

Resemblances.—Serpentine resembles Chalcedony to some extent, but has none of the radiating and concentric structure of that mineral. Chlorite may usually be distinguished by its cleavage or vermicular habit.

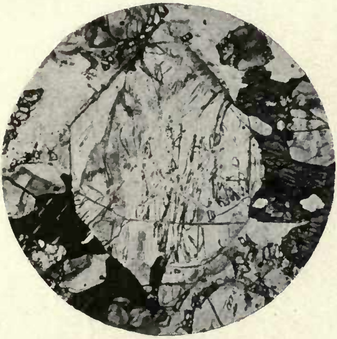
PLATE IX



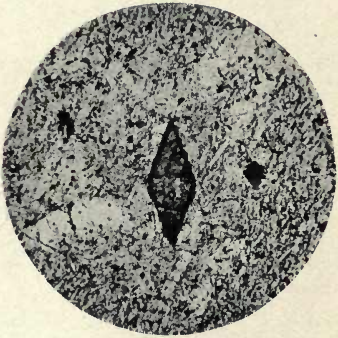
1.—Olivine. Ordinary Light. Showing form and alteration.



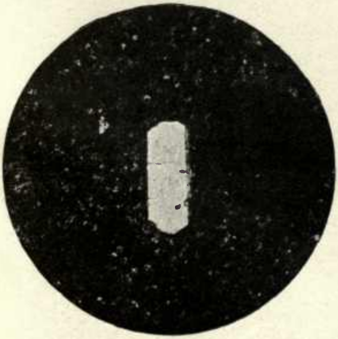
2.—Olivine. Ordinary Light. Showing form and more advanced alteration.



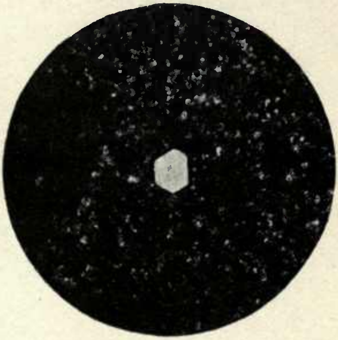
3.—Serpentine. Ordinary Light. Pseudomorph after Olivine.



4.—Sphene. Ordinary Light. Showing form and high refractive index.



5. Apatite, vertical section. Ord. L. Showing form and cleavage.



6.—Apatite, basal section. Ordinary Light. Showing form.

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Apatite.—$Ca(F,Cl)Ca_4(PO_4)_3$. *Hexagonal. Cleavage Basal. Birefringence negative.*

Colour.	None.
Form.	Transverse sections regular hexagons, vertical sections lath-shaped.
Cleavage.	Occasionally seen in vertical sections.
Ref. Index.	1·64. Good relief.
Alteration.	None.
Pol. Colours.	1st order grey; basal sections, isotropic.
Extinction.	Straight.
Twinning.	None.

Resemblances.—This mineral ought not to be mistaken for any of the foregoing; it is distinguished from nepheline by its refraction, and from olivine by its polarisation and form.

Sphene (Titanite).—*Silicate and titanate of calcium. Monoclinic. Twin plane* 100 (*orthopinacoid*). *Birefringence positive.*

Colour.	Yellowish-brown or greyish-brown.
Form.	Often lozenge-shaped—like an elongated ace of diamonds—but the form is not always well-developed.
Cleavage.	Rarely seen.
Ref. Index.	1·89. High relief and pitted surface.
Pleochroism.	Sometimes distinct, but usually feeble.
Pol. Colours.	High order greys. These, however, are so pale that the polarisation colour does not appear to be appreciably different from the absorption colour.
Twinning.	Not common, but sometimes simple twins are seen.

Resemblances.—When idiomorphic, no difficulty whatever is experienced, but other examples may exhibit some resemblance to augite. The differences of refraction and polarisation, however, should always serve to distinguish between them, even when the obvious peculiarities of form are absent.

Garnets.—$R_3''R_2'''(SiO_4)_3$. *The Garnets form an isomorphous group of minerals which are here taken together for convenience. Each is a silicate of at least two metals, one divalent and one trivalent, the positive elements represented in the group being calcium, magnesium, iron, manganese, aluminium and chromium. Cubic.*

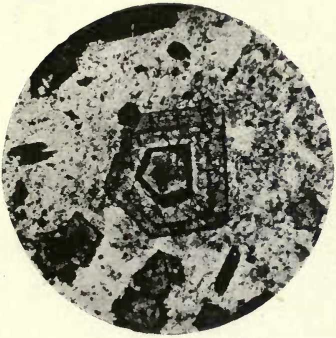
Colour.	Pink, colourless, or brown.
Form.	Commonly rounded, but occasionally polygonal.
Cleavage.	Rarely seen, but irregular cracks are common.
Ref. Index.	1·76 to 1·83. Good relief.
Alteration.	None.
Inclusions.	Sometimes present in abundance.
Pleochroism.	None.
Pol. Colours.	Isotropic in nearly all cases.

Resemblances.—The isotropism will usually serve to distinguish garnet from any of the other highly refracting minerals in the preceding list.

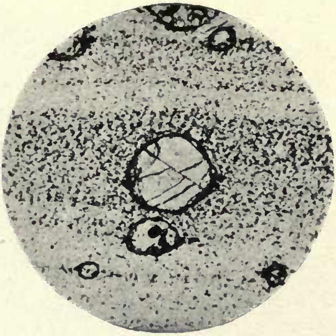
Tourmaline. — *Boro-silicate of aluminium, with magnesium, iron and alkali metals. Hexagonal. Birefringence negative.*

Colour.	Commonly brown, but may be yellow, green, blue, or colourless. Often the colour is irregular in its distribution, different portions of a single fragment being differently coloured.
Form.	Transverse sections triangular or hexagonal. Vertical sections elongated, and even sometimes acicular. Often in irregular masses.
Cleavage.	None; but an imperfect basal fracture is sometimes seen in vertical sections.
Ref. Index.	1·63. Fairly good relief.

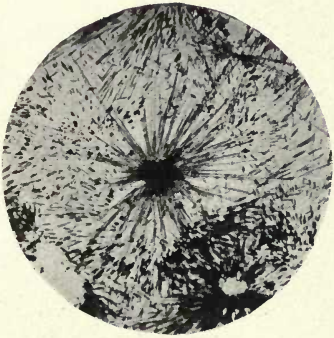
PLATE X



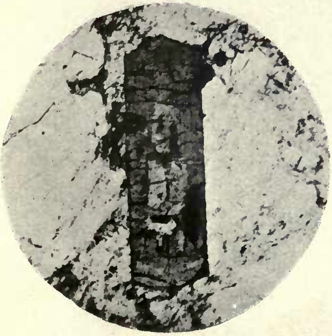
1.—Garnet (Melanite). Ordinary Light. Showing form and zoning.



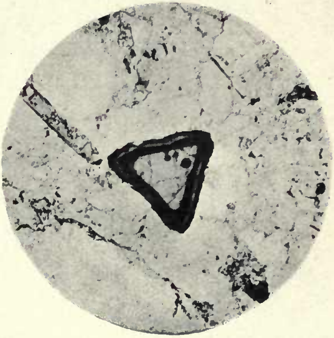
2.—Garnet. Ord. L. Showing rounded form and high refractive index.



3.—Tourmaline. Ord. L. Showing acicular and radiating habit.



4.—Tourmaline, vert. section, Ordinary Light. Showing form.



5.—Tourmaline, basal section. Ord. L. Showing form and zoning.

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Alteration.	None.
Pleochroism.	Vertical sections with colour are strongly pleochroic; oblique sections feebly pleochroic, and basal sections non-pleochroic. The possibility of the absence of pleochroism should be borne in mind when examining fragments whose orientation is not known. In well-formed vertical sections, it will be observed that when the length is arranged in a N.S. direction the maximum absorption is taking place.
Pol. Colours.	2nd order colours common; but when the absorption is strong, polarisation colours are obscured. Basal sections isotropic.
Extinction.	Straight.
Twinning.	None.

Resemblances.—When the crystals are small, vertical sections of brown tourmaline resemble biotite or hornblende; but either of these may be distinguished from tourmaline by an application of the pleochroism test. The dark extreme of tourmaline is seen when the length is N.S. The dark extreme of biotite or hornblende is seen when the length is E.W.

Topaz. — $(AlF)_2SiO_4$. *Orthorhombic. Cleavage parallel to* 001 *(basal). Birefringence positive.*

Colour.	None.
Form.	Usually rounded or irregular.
Cleavage.	Rarely seen.
Ref. Index.	1·62. Good relief.
Alteration.	None.
Pol. Colours.	1st order.
Twinning.	None.

Resemblances.—The characters of topaz are much like those of quartz, and some difficulty is experienced in making the distinction. An exhibition of cleavage settles the point at once in favour of topaz, but it is not often available; the most useful distinction is that of refractive index—a distinction which students should lose no time in endeavouring to appreciate. The minerals may also be distinguished in convergent light.

THE SILICATES OF ALUMINIUM

There are three important minerals coming in this group:—

Andalusite.	*Orthorhombic.*
Sillimanite.	*Orthorhombic.*
Kyanite.	*Triclinic.*

Andalusite.—$Al(AlO)SiO_4$. *Cleavage* 110 (*Prismatic*). *Birefringence negative.*

Colour.	Pale pink or colourless.
Form.	Usually in rounded grains, but occasionally showing rhomb-shaped or elongate sections.
Cleavage.	Rarely seen.
Ref. Index.	1·64. Good relief.
Pleochroism.	Pale pink to colourless.
Pol. Colours.	1st order greys.
Twinning.	None.

Resemblances.—The mineral resembles apatite somewhat closely, but the pale pink colour and the form, together with the absence of isotropic sections, are useful means of distinction. Also distinguished by biaxial figure in convergent polarised light.

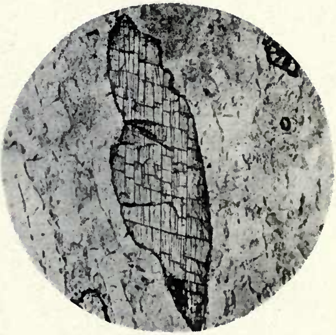
Chiastolite is a variety with characteristic inclusions.

Sillimanite.—Al_2SiO_5. *Cleavage* 010 (*Brachypinacoid*). *Birefringence positive.*

Colour.	None.
Form.	Commonly acicular, but sometimes irregular.

PLATE XI

1.—Chiastolite, basal section. Ord. L. Showing form and inclusions.



2.—Kyanite. Ord. L. Showing cleavages and high refractive index

3.—Epidote. Ordinary Light. Showing form and cleavage.

4.—Epidote. Ordinary Light. Showing occurrence in amygdule.

To face page 85.

Cleavage.	Rarely seen.
Ref. Index.	1·67. Good relief.
Pol. Colours.	1st and 2nd order.

Resemblances.—Distinguished from apatite by its higher polarisation colours, and by biaxial figure in convergent light.

Kyanite.—$(AlO)_2SiO_3$. *Cleavage* 100 (*Macropinacoidal*) *and* 010 (*Brachypinacoidal*). *Birefringence negative.*

Colour.	Pale blue.
Form.	Irregular.
Cleavage.	Usually well seen in one direction. Occasionally two are seen.
Ref. Index.	1·72. Good relief.
Pleochroism.	Feeble—pale blue to colourless.
Pol. Colours.	1st and 2nd order.

Resemblances.—The colour, cleavage, and refractive index, are sufficient to distinguish the mineral from any other. Hauyne is sometimes blue, but the colour is almost the only point of resemblance. Glaucophane is distinguished by its lower refractive index and higher polarisation colours.

Epidote.—$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$. *Monoclinic. Cleavage* 001 (*Basal*). *Twinned on* 100 (*Orthopinacoid*). *Birefringence negative.*

Colour.	Pale yellow green (pistachio green).
Form.	Usually granular or irregular. Occasionally idiomorphic, with transverse sections exhibiting resemblances to those of hornblende.
Cleavage.	In one direction, but not always seen.
Ref. Index.	1·76. Very good relief.
Pleochroism.	Feeble: pale green to darker green.
Pol. Colours.	2nd and 3rd order. Very bright colours.
Twinning.	Rarely seen.

Resemblances.—Epidote is distinguished from pyroxenes and amphiboles by its colour and higher refractive index; from sphene and garnet by its bright polarisation. Tourmaline is sometimes very similar in appearance when in irregular masses, but epidote may be distinguished by its peculiar colour, superior cleavage, higher refraction, or brighter polarisation; and in convergent light by its biaxial interference figure.

Zoisite. — $Ca_2(AlOH)Al_2(SiO_4)_3$. *Orthorhombic. Cleavage* 010 *(Brachypinacoid). Birefringence positive.*

A mineral closely related to epidote in composition, but differing very widely from it microscopically.

Colour.	Usually none.
Form.	Variable.
Cleavage.	Rarely seen.
Ref. Index.	1·70.
Pol. Colours.	1st order grey or ultra-blue.

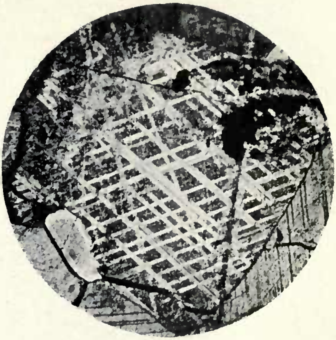
Resemblances.—Distinguished from apatite by absence of form, higher refractive index, or ultra-polarisation; also by its biaxial interference figure.

Calcite.—$CaCO_3$. *Hexagonal. Cleavage Rhombohedral. Birefringence, negative.*

Colour.	None.
Form.	None.
Cleavage.	Good. In two or three directions.
Ref. Index.	1·57 approx.; but varies with the direction of section.
Alteration.	None.

PLATE XII

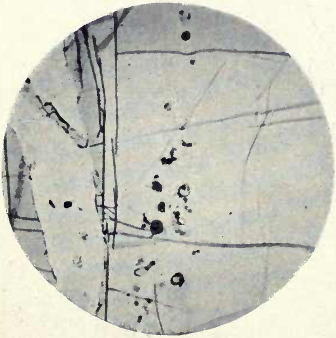
1.—Calcite. Ord. L. Showing cleavages and the occurrence in amygdule.



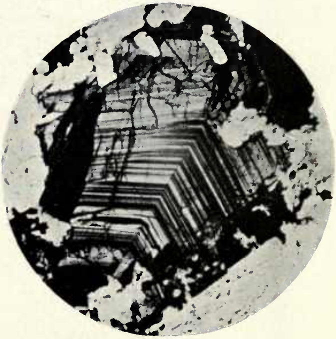
2.—Calcite. Crossed nicols. Showing lamellar twinning.

3.—Dolomite. Ordinary Light. Showing form and zoning.

4.—Zeolites. Ord. L. Showing occurrence with vermicular chlorite in amygdule.



5.—Cordierite. Ordinary Light. Showing haloes around inclusions.



6.—Cassiterite. Ordinary Light. Showing zoning.

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Pleochroism.	None. But there is often a striking change of relief when the test is applied, the result of the high double refraction. This change, when the polariser or the stage is rotated rapidly, gives the effect known as twinkling.
Pol. Colours.	Pale pinks and greens or high order greys.
Twinning.	Lamellar.

Dolomite.—$CaCO_3MgCO_3$. *Hexagonal.*

Has many points of resemblance to calcite, but has crystals with a rhomb-shaped outline, and often well-marked colour zoning.

Zeolites.—*Hydrated silicates of aluminium with various alkalies and alkaline earths.*

The group known as Zeolites is a very large one, the different individuals differing greatly. They are secondary minerals, found filling cracks or cavities.

They are colourless, and have a refractive index near to that of Canada balsam. Two of the most important are ANALCIME (cubic) and NATROLITE (orthorhombic); the latter occurs as acicular crystals polarising in 1st order colours. Analcime may occur in cavities as a secondary mineral, but it is sometimes found in igneous rocks in circumstances which suggest that it is a primary constituent.

Cordierite.—*Silicate of magnesium, iron, and aluminium. Orthorhombic. Cleavage* 100, 010, & 001 (*macro-, brachy-, and basal pinacoids*). *Birefringence negative.*

Colour.	None.
Form.	Usually allotriomorphic.
Cleavage.	Not conspicuous, but may often be seen.
Ref. Index.	1·54. Almost equal to that of Canada balsam.

Alteration.	Commonly alters along cracks, forming turbid, pale greenish streaks.
Pleochroism.	None, save around minute inclusions, which often produce beautiful pleochroic haloes.
Pol. Colours.	1st order.
Twinning.	Occasionally seen. Simple or lamellar.

Resemblances.—May be distinguished from quartz and felspars by the pleochroic haloes, which, although not necessarily conspicuous, may nearly always be found; also distinguished from quartz by its cleavages, twinning, and biaxial interference figure.

Cassiterite (Tinstone).—SnO_2. *Tetragonal. Twinned on* 101 (*2nd order pyramid*). *Birefringence positive.*

Colour.	Brown.
Form.	Usually irregular or granular.
Cleavage.	None.
Ref. Index.	2·00. Very high relief.
Zoning.	Colour zoning common and well shown.
Pleochroism.	Feeble.
Pol. Colours.	High order greys, but usually masked by the body colour.
Twinning.	Simple twins common.

Zircon.—$ZrSiO_4$. *Tetragonal. Twinned on* 101 (*2nd order pyramid*). *Birefringence positive.*

Very much like apatite, but distinguished by its higher ref. index (1·95), and by its polarisation colours. These latter are high order greys, with, in a few cases, pale pinks and greens of a high order. The distinction between the two minerals is not an easy one, as the greys of a high order may be very similar to those of the 1st order shown by apatite, but the distinction may be effected by the form of the cross sections and the sign of double refraction.

THE OPAQUE MINERALS

Magnetite.—$FeOFe_2O_3$. *Cubic.*

Titanoferrite.—$FeTiO_3$. *Hexagonal.*

Pyrites.—FeS_2. *Cubic.*

As these minerals are opaque, it will be seen that the only available method of examination is that by reflected light.

Pyrites, thus examined is seen to be brass yellow.

Magnetite and titanoferrite are black when fresh, but when decomposed, the one can be distinguished from the other. The alteration product of magnetite is brown or yellow, that of titanoferrite is white, and its development has often taken place so as to form triangular geometrical patterns.

REFRACTIVE INDEX OF ISOLATED FRAGMENTS

REFRACTIVE INDEX OF ISOLATED FRAGMENTS

In considering the appearance of minerals in thin section as observed in ordinary transmitted light, it was seen that some idea as to the refractive index of a mineral could be obtained by inspection of the surface and margin of a fragment, comparison being made between the refractive index of the mineral fragment and that of the mounting medium, Canada balsam. A test for determining whether the mineral had a higher or lower refractive index than that of the Canada balsam was also given.

As a means of determining the refractive index of a mineral, the method is obviously inadequate, for the reason that, after having determined its position in the scale (whether higher or lower) with reference to Canada balsam, one has to rely on the degree of relief in order to approximate to the real value. The inadequacy of the method is inevitable since Canada balsam is the only satisfactory mounting medium. If, however, isolated fragments of the mineral are available for examination, these may be immersed and examined successively in liquids differing from one another, and each having a known value of refractive index.

The following liquids will be found useful :—

Water	1·34
Alcohol	1·36
Chloroform	1·45
Olive Oil	1·47
Castor Oil	1·48
Xylol	1·49
Oil of Cedar Wood	1·51
Monochlorbenzol	1·53
Oil of Cloves	1·54
Brom-toluene	1·55
Dimethylaniline	1·56
Orthotoluidine	1·57
Aniline or Cinnamon Oil	1·59
Cassia Oil	1·60
Iodobenzene	1·62
Monobromonaphthalene	1·66
Methylene Iodide	1·74

The fragments of a given mineral (which may be as small as the head of a pin) may be examined in turn in a small pool of each of these liquids; the refractive index of the mineral being approximately equal to that of the liquid in which its outline is least conspicuous.

That method of procedure, however, is not the best either as regards accuracy or speed. It is more satisfactory to have a means of comparing the refractive index of mineral and liquid. This comparison may in some cases be effected by using

Becke's test, but the shape of the fragment is not, as a rule, such as to give good results. A method more adapted to the requirements of the case is that known as the shadow method.

Make a small pool of the liquid (oil of cloves is convenient for a first experiment) on an ordinary microscope slip, transfer the mineral to the pool by means of a small brush, taking the precaution to ensure complete immersion, and examine microscopically under the low power objective in ordinary transmitted light. Then slide the finger underneath the stage until part of the light is cut off. The field will, of course, be partially darkened, but the shadow affecting a great portion of the field is to be ignored; the observer should concentrate his attention on the edges of the mineral fragment. It will be found as a rule that a black shadow appears *on* one side of the fragment. If the shadow appears on the same side as that on which the finger is inserted, the refractive index of the mineral is higher than that of the liquid; if the shadow appears on the opposite side, the refractive index of the mineral is lower than that of the liquid.

Mineral>liquid.

Mineral<liquid.

The two cases figured are drawn on the assumption that a finger of the right hand is employed to cut off the light.

A slight variation in the method is desirable in using the more mobile liquids, such as xylol; such liquids are not sufficiently viscous to secure complete immersion of the mineral fragment when used on an ordinary microscope slip, and it is therefore desirable to use a watch glass.

Let it be supposed that the experiment has demonstrated that the refractive index of the mineral $> 1 \cdot 54$. Experiment should then be made with a liquid near the upper end of the scale in order to find, if possible, two extreme values between which the mineral must lie, or, failing this, to demonstrate that the mineral has a very high refractive index. A convenient highly refracting liquid is monobromonaphthalene; methylene iodide, as it rapidly darkens on exposure to light, should only be used when absolutely necessary. If it is found that the refractive index of the mineral is $< 1 \cdot 66$, then observations should be taken, using liquids coming between these two extremes, until the position of the mineral has been fixed within the narrowest possible limits.

It will be seen in some cases, that instead of resulting in a definite shadow, the insertion of the finger produces colour fringes, which always indicate a close approximation between the values of mineral and liquid. Their production results from the fact that the liquid is much more strongly dispersive than the solid. In difficult cases it is advisable to perform the experiment by the light of a sodium flame instead of ordinary daylight, as the refractive indices of the liquids were determined with light of that particular wave length.

It will be seen that such a method of determining one of the optical constants of a mineral is extremely useful when an identification has to be made; and it has the merit that only a very small quantity of the mineral is required.

HINTS ON PETROLOGY

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IGNEOUS ROCKS.—In the classification of igneous rocks, two groups of facts are to be considered, (a) the mineralogical constitution, and (b) the degree of crystallisation.

It is the infinite variety that usually bewilders the student, but the rocks may be grouped in such a way as to minimise the difficulties to a great extent. The best way in which to approach the subject is to consider the igneous rocks to be arranged for purposes of classification in a cabinet provided with pigeon-holes, each compartment containing many rocks more or less resembling a certain type. Later study will teach the student that the partitions have no existence in fact, but they will have served their purpose; the rocks will still be grouped around types, but the different groups will be seen to merge one into the other.

It is well to commence with the study of those igneous rocks known either as plutonic, in reference to their mode of origin, or as holocrystalline, in reference to their texture.

As the latter name implies, these rocks are made up entirely of crystalline constituents. They are arranged in four great groups, known respectively as Granite, Syenite, Diorite and Gabbro. The fundamental distinction between these rocks is a chemical one, based on a consideration of the percentage of silica present.

Granite	contains $>$ 66% of SiO_2	Acid
Syenite Diorite	contain between 52% and 66% of SiO_2	Intermediate.
Gabbro	contains $<$ 52% of SiO_2	Basic

They are referred to as acid, intermediate, and basic, in reference to the silica percentage, most of the constituents being silicates.

It is obviously impossible to estimate the silica percentage accurately by means of the microscope, but an approximation which is sufficiently satisfactory may be made when the minerals present are identified, and when the proportions in which they are present are considered.

The first duty of the investigator, then, is to determine the minerals present; the second, to form some idea of the proportion represented by each.

Granite.—The only two essential constituents are quartz and orthoclase felspar; but in the different varieties of granite there are many other possibilities. The typical granite is made up of quartz, orthoclase, muscovite, and biotite; but although all varieties contain the first two minerals, the micas are not necessarily present. The granite may contain one of these only, or they may be replaced by green hornblende. Other possible minerals are microcline, plagioclase, felspars, such as albite and oligoclase, sphene, apatite, andalusite, tourmaline, topaz, tinstone, garnet, zircon, magnetite. It will be seen that there are many possible varieties, but all contain quartz in abundance, together with orthoclase felspar.

The members of the Albite-Anorthite series, rich in soda, may be present, but not those rich in lime. This fact makes it desirable to have some simple means of distinction between the different members of that series. Unfortunately, such a simple test is not available; the investigator has to make the most of the facts that the members near the albite end of the series have a refractive index near to that of Canada balsam, and a small angle of extinction as measured from the twin planes. The different varieties may be named biotite granite, hornblende granite, tourmaline granite, etc., according to the particular non-essential constituent present in abundance. A special name, Greisen, is given to a topaz granite.

Syenite.—A typical Syenite is made up of orthoclase and hornblende, but the orthoclase only is essential; biotite may be present to the exclusion of hornblende. The chief point to bear in mind, however, is abundance of the alkalies, which is reflected in the composition of the felspars. As has been said, orthoclase is essential, but microcline and soda felspars are very commonly present in addition. Quartz may be present in small quantity in some varieties; the felspathoids sodalite and elæolite in others; but free silica and felspathoids are never found together, as they represent variations from the type in two opposite directions.

The possible minerals, then, are orthoclase, microcline, soda felspars, elæolite, sodalite, hornblende, biotite, a green pyroxene, quartz, sphene, apatite, zircon, the brown garnet melanite, and magnetite.

The typical syenite is distinguished from a granite by the absence or scarcity of quartz. The felspathoid syenites are clearly marked off from granites, since the latter never contain felspathoids.

The varieties are distinguished as boitite, augite, quartz, elæolite-syenites, etc.

Diorite.—The typical Diorite contains a soda-lime or lime-soda felspar approximating to andesine in composition, together with hornblende. Its most striking difference from granite is that it contains no quartz; from syenite, it differs in the nature of its felspars, and the invariable absence of felspathoids. The possible minerals are oligoclase, andesine, labradorite, hornblende, biotite, augite, enstatite, quartz, apatite and magnetite.

The quartz diorites approximate to granite, and the oligoclase diorites to syenite.

Gabbro.—Lime felspar and diallage are typical of this group. Other possible minerals are hornblende, olivine (altered to serpentine (?)), hypersthene, apatite, magnetite and ilmenite (titanoferrite). The felspar is characterised by a fairly high refractive index and a high extinction angle. Gabbro differs from Diorite in the possession of a more basic felspar and abundant pyroxene.

In addition to the minerals enumerated, the felspars more rich in soda, orthoclase, and nepheline must be included as possibilities in some gabbros which are somewhat abnormal in their alkali content. Such rocks must be placed with the gabbros since their silica percentage is less than 52, but they approximate to the Syenites in composition. Some varieties are olivine gabbro, hypersthene gabbro, and alkali gabbro.

The possible occurrence of felspathoids is a point of resemblance between gabbros and syenites, a possibility which clearly marks them off from the granites and diorites.

SUMMARY.

Granites	Much quartz, alkali felspar, little hornblende or biotite.
Syenites	Much alkali felspar, little hornblende or biotite.
Diorites	Lime-soda or soda-lime felspar, hornblende.
Gabbros	Lime felspar, diallage, sometimes olivine.

The above summary is intended as a guide only. It does not cover all the possibilities, but, used in conjunction with a more extended description, will be found useful. Cases will be met which appear to partake equally of the characters of two or more of these groups, and difficulty will be experienced in classifying such rocks. Only practice, however, will enable the student to deal confidently with difficult examples.

The above groups of rocks: granites, syenites, diorites, and gabbros, are all holocrystalline, and have been formed in circumstances where very slow cooling took place. In other circumstances, similar molten material cooled more rapidly. The loss of heat was in extreme cases so rapid, that crystallisation was impossible, and the product was non-crystalline or "glassy." As different circumstances led to different rates of cooling, different degrees of crystallisation are found in the case of each group. This difference of texture has had an influence on the scheme of classification; and, as indicated, the present scheme has the two-fold basis:—composition and texture.

The acid rocks include:—

Granite	plutonic
Granite Porphyry	hypabyssal.
Quartz Porphyry	
Quartz Felsite	
Rhyolite	volcanic.
Pitchstone	
Obsidian	

The intermediate rocks (syenite series) include:—

Alkali Series.	Elæolite Syenite.	Syenite	plutonic
		Syenite Porphyry	hypabyssal.
		Orthoclase Porphyry	
		Felsite	
	Phonolite	Trachyte	volcanic.
		Trachytic Pitchstone	

The intermediate rocks (diorite series) include:—

Diorite	plutonic.
Diorite Porphyry	hypabyssal.
Porphyrite	
Andesite	volcanic.
Andesitic Pitchstone	

The basic rocks include:—

Alkali Series	Alkali Gabbro	Gabbro	plutonic.
		Dolerite	hypabyssal.
	Alkali Basalt.	Basalt	volcanic.
		Tachylyte	

In each series the minerals present (if any) are the same as in the plutonic rock at the head of the list.

A description of the various textures met with in these types is not within the scope of this work; the student will learn all the facts by an examination of a well-selected series of rocks and sections. It may, however, be pointed out that the basic rocks have a much greater tendency to crystallise than have the acid rocks; basalt, for instance, is much better crystallised than rhyolite, although the conditions of formation may have been very similar in the two cases.

Ultra-Basic Group.—This ill-defined group includes those rocks which are extremely poor in silica, and which, as a rule, may be looked upon as basic rocks with an unusually large proportion of ferro-magnesian silicates. The rocks do not admit of such a satisfactory grouping as those previously considered.

Many names have been given to individual rocks which differ very slightly from one another, but they may conveniently be placed into groups, the group name indicating the nature of the rock satisfactorily. The tendency to crystallise is still more strongly marked than in the basic rocks.

PLUTONIC & HYPABYSSAL.

Pyroxenites	consist largely of pyroxene.
Hornblendites	consist largely of hornblende.
Eclogite	consists of green pyroxene, green amphibole and red garnet.
Picrites	consist of olivine, augite, and sometimes a little felspar. Some varieties contain hornblende in addition to, or instead of, the augite.
Peridotites	consist largely of olivine.
Serpentines	consist largely of serpentine which may have been produced by the alteration of olivine, pyroxene, or amphibole.

VOLCANIC.

Augitite	consists of augite and magnetite.
Limburgite	consists of augite, magnetite, and olivine.

SEDIMENTARY ROCKS.—The operations of denudation and deposition are so completely bound up with the appearances presented by these rocks that it is quite hopeless to attempt their study without a good knowledge of physical geology. That knowledge will be assumed, and only the lines on which the examination of thin sections should proceed will be indicated.

Hand-specimens should always be examined if available.

Arenaceous Rocks (pebbly and sandy).—Thin sections of pebbly rocks do not often convey much information, since a section cut from one fragment may differ completely from another on account of the marked heterogeneity of such a rock.

Sandy rocks, however, may often be examined with profit. As a result of their mode of formation, there has usually been such a selection of mineral fragments that the bulk of these derived constituents is made up of minerals which are not decomposed by trituration in atmospheric waters; and as quartz is by far the most common of these, that mineral is the most important constituent. Other stable minerals occur, but are much less common; muscovite, tourmaline, garnets, cassiterite and zircon, are the most important. In those cases, however, where the accumulation of the detritus to form the deposit was not accompanied by much water action, less stable minerals had a chance of preserving their identity; and felspars make up a considerable proportion of such rocks.

In general, the fragments are more or less angular, but, in a few cases, it is found that they are completely rounded—usually to be regarded as an indication of wind erosion and accumulation under desert conditions.

The material holding these grains together (the cement) is commonly silica, calcium carbonate, or iron oxide, and forms a very characteristic feature of such rocks. In a microscopic investigation of such a rock, the derived fragments and the cementing material should be identified, and some attempt should be made to visualise the conditions under which accumulation took place.

If a hand-specimen is available, further information as to the nature of the constituents may be obtained if the fragments are examined in the series of liquids for determining refractive indices. Such a method of examination is specially valuable in regard to the constituents of these rocks since, as all the fragments have been eroded, the test of form is no longer available.

Argillaceous Rocks.—Slates and shales are usually so fine-grained that even the microscope usually fails to reveal much as to their mineral composition. Some examples, however, seem to show that their constituents are very much like those of arenaceous rocks, the fragments merely being ground down to much smaller dimensions. Crystals of pyrites, of fairly large size, are sometimes found, but these have been formed in consequence of changes which have taken place since deposition.

Calcareous Rocks.—These rocks are, as a rule, organic in origin, although some of them, such as stalactite and travertine, are formed simply by deposition from solution. Oolitic limestones are probably also inorganic in origin, the calcium carbonate of the oolite having been deposited in successive layers around a nucleus. Calcite makes up the bulk of such rocks, and may easily be recognised as such by the twinkling effect observed when the section is examined under the microscope with the lower nicol only, and by the absence of crystal form. The organisms of which the rocks are largely built are usually clearly visible, and may be identified by those who have a sufficient knowledge of palæontology. Foraminifera, such as Globigerina and Nummulites, are sometimes important limestone builders; corals, crinoids, and various molluscs are also of primary importance.

Some of the calcareous rocks consist entirely, or to a great extent, of the mineral dolomite, which, although resembling calcite in many respects, may be distinguished by its tendency to occur in well-defined rhombs, and its frequent colour zoning. As a rule, fossils are not seen in dolomite. Somewhat similar rocks are those consisting partly of calcite and partly of dolomite. Some of these rocks owe their heterogeneity to the fact that they are partially dolomitised limestones, the magnesium having been added since the rock commenced its existence as a limestone.

Siliceous Rocks.—There are two methods of formation. (1) The material accumulated as a deposit of the remains of organisms (*e.g.*, radiolaria), with siliceous skeletons, sometimes sufficiently well-preserved to be identified, and (2) the rock represents a silicified limestone, silica from solution having replaced a pre-existing limestone. In this latter case, the structures of the limestone may be preserved. Tripoli and some cherts owe their formation to the accumulation of siliceous organisms; flint, some cherts, and such rocks as siliceous oolites, to a process of replacement.

The silica of these rocks is usually in the form of quartz, but may be chalcedony or opal. It is in the form of opal that woody tissues are so often preserved.

Carbonaceous Rocks.—These rocks, as a rule, do not repay examination in thin section; but a few of the Carboniferous coals exhibit the remains of the spores and spore-cases of the Lycopods of that period. Other plant tissues are also occasionally revealed by this method of investigation.

The distinction between sedimentary and igneous rocks, as seen in the microscope, is sometimes a matter of some difficulty. The two classes overlap in the rocks known as tuffs. These are volcanic in origin, but they partake of the nature of sediments, even to the extent of including fossils. A rock with fossils may, if we except the case of tuffs, safely be considered to be of sedimentary origin. Some difficulty is often encountered in the case of the arenaceous rocks, which may show marked resemblance to igneous rocks; this applies particularly to the case of felspathic sandstones, where a cementing material is not always conspicuous. Even bedding is not to be relied upon as a proof of sedimentary origin, since some rhyolites exhibit structures which simulate that character very closely.

METAMORPHIC ROCKS. — The most striking feature of these rocks is their foliation, a structure which, superficially, may resemble bedding; but a microscopic investigation should always enable the student to make the distinction. This arrangement of the constituent minerals in layers, however, is not always exhibited, and is often inconspicuous. Some of the rocks are holocrystalline, and are only to be distinguished from igneous rocks by their foliation, which, it should be remembered, is often more conspicuous in hand specimen than in section.

Although many minerals are found both in igneous and metamorphic rocks, some are found almost invariably only in the latter group, and are therefore very useful when present. Such minerals are chiastolite, sillimanite, kyanite, cordierite, tremolite, actinolite, glaucophane, forsterite, talc, and zoisite; garnets also, particularly those containing lime, are much more common in metamorphic than in igneous rocks. Other minerals found commonly, but not exclusively, in metamorphic rocks are quartz, felspars, micas, chlorite, diopside, epidote and calcite.

All stages of crystallisation are found in metamorphic rocks, the particular stage reached being dependent on the nature of the original rock and the amount of change it has undergone.

The most important metamorphic rocks are:—

Gneisses.— Characterised by their holocrystalline nature, and, as a rule, by a coarse foliation and abundance of felspar. The varieties receive the name of granite-gneiss, diorite-gneiss, etc., according to the plutonic igneous rock they most closely resemble. A special structure-variety is that known as augen-gneiss, from the eye-like fragments of a conspicuous mineral—usually felspar.

Schists.— Conspicuously foliated, holocrystalline rocks, from which felspar is absent or not abundant, and in which the folia are thinner than in gneisses. They are named according to some mineral which is abundant, as mica-schist, hornblende-schist, chlorite-schist, talc-schist, quartz-schist, etc.

Some rocks which were originally argillaceous sediments, and in which metamorphosis has not been carried to any great extent, are chiastolite slate, phyllite, and spotted slate.

Granulites.— Holocrystalline, inconspicuously foliated, and consisting of more or less rounded mineral grains, forming a mosaic. The rock is named from some conspicuous constituent, as pyroxene-granulite, kyanite-granulite, etc.

Crystalline Limestones.—Consisting to a greater or less extent of crystalline calcite. The rocks were originally more or less impure limestones, and the existing rock is the result of the re-arrangement of the constituents. Specially instructive cases are those in which the rock consists of calcium and magnesium silicates, calcite, and magnesium oxides. They are the result of the metamorphism of an impure dolomite, the process being known as dedolomisation.

In the endeavour to determine the nature of the rock from which a metamorphic rock was derived, the student must bear in mind that the changes effected have, as a rule, been changes merely of arrangement of constituents—not changes in the composition of the rock as a whole. It is therefore of considerable importance that he should be familiar with the composition of the more common minerals. Such knowledge will help him materially in his task of harmonising his isolated scraps of knowledge regarding rocks—a task which all students should undertake. Exceptions to the general rule, however, are found in the case of the rocks which contain such minerals as tourmaline, topaz, cassiterite, and some micas. These minerals, together with many others, most of them characterised by the presence of fluorine or boron, usually owe their origin to a process of pneumatolysis, a process which necessarily involves transport of material from one rock to another in the form of vapour.

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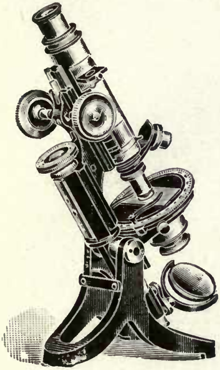

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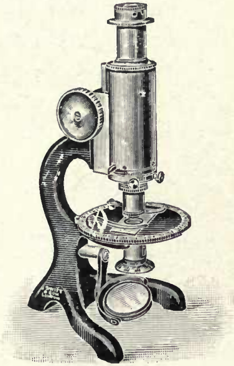

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